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THE PHYSICAL BASIS OF NERVE FUNCTIONS

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I. INTRODUCTION

Modern experimental investigations of the laws governing nervous action, combined with theoretical studies based upon these investigations, provide us with the materials for a very definite and satisfactory conception of the physical mechanism of the process. It is the purpose of the present article to sketch a rough picture of the probable nature of this mechanism, in the hope that the sketch may prove valuable to some psychologists who may not have followed closely modern developments in this field. I do not wish to claim any essential originality for the general ideas to be presented, although it is my belief that the total picture which I shall outline has not been offered heretofore and that some of the suggestions which will be made concerning details are new. My views are founded mainly upon the writings of Nernst,¹ R. S. Lillie,² and Lucas.³

II. THE GENERAL MECHANISMS OF EXCITATION AND STIMULATION

It was for a long time suspected that the nerve impulse is essentially an electrical phenomenon, since the electrical

¹ Nernst, W., 'Zur Theorie des elektrischen Reizes,' *Arch. f. d. ges. Physiol.*, 1908, 122, 275-315; and other papers.

² Lillie, R. S., 'The Relation of Stimulation and Conduction in Irritable Tissues to Changes in the Permeability of the Limiting Membranes,' *Amer. J. of Physiol.*, 1911, 28, 197-223; and other papers.

³ Lucas, K., 'The Conduction of the Nervous Impulse,' London, 1919. Also many papers.

action current of a nerve provided the only direct evidence of the existence of the impulse. Paradoxically enough, this index of excitation consists not in the appearance of a state of electrification in the nerve but rather in the partial disappearance of such a state which is already present in the resting cell; and which manifests itself through the 'current of rest' or 'demarcation current,' obtained when the cut end or injured surface of the nerve is connected through a galvanometer to the nerve sheath. The current flows from the sheath to the injured portion, indicating that the former is positively charged with respect to the latter. When the nerve cell is excited this positive electrification of the sheath decreases momentarily.¹

The electrical theory of matter, and in particular the so-called theory of 'electrolytic dissociation'² offers us the materials for a simple explanation of the resting electrification of the nerve. A nerve fiber, like almost any other living cell, consists of an aqueous solution of many substances, both organic and inorganic. Among these are substances which become *ionized* in solution, that is, their individual molecules are broken up into electrically charged particles, positive and negative ones being produced in equal numbers. Prominent among ions of this sort are to be counted those of carbonic acid, the substance which is produced by the respiratory function of the cell. The ionic particles, in common with all of the molecules of the cell, are endowed with a rapid vibratory motion which represents the temperature or thermal energy of the substance. In accordance with the general theory of solutions, the motion of the dissolved particles among the molecules of the solvent, water, resembles that of the molecules of a gas in free space. This means that they must exert a pressure upon any surface which tends to interfere with their free diffusion.

¹ A simple account of the electrical phenomena exhibited by nerve and muscle will be found in Howell, W. H., 'A Text-Book of Physiology,' 1909, Chap. IV., pp. 96-110.

² For a simple presentation of the essentials of the modern electrical theory of matter, reference may be made to the book by the writer and D. F. Comstock, 'The Nature of Matter and Electricity,' 1917. On 'electrolytic dissociation' see pages 139-141, and on pressure due to molecular motion see pages 106-109 of this work.

The liquid mass of the cell is contained within a membrane which may be conceived as a more or less solid envelope. This membrane is not necessarily to be identified with the myelin sheath in the case of the nerve fiber, and it may simply consist in some peculiar condition of the molecules at the surface of the general cell mass. In general the bounding surfaces of liquid masses behave like actual membranes. Now it is obvious that the ions in the general cell mass will exert an outward pressure on this membrane, especially as there is probably an aqueous medium outside as well as inside of the cell. If the membrane is absolutely tight or *impermeable* to these ions there will simply be a tendency to distend it, but if on the other hand the membrane is somewhat porous certain of the ions may pass through. It is clear that small ions will pass through more readily than large ones, and in the case of those of carbonic acid the hydrogen ions will almost certainly be the smaller. Hydrogen is the smallest of the atoms and its positive ion is probably the smallest of all known physical particles. If bare hydrogen ions occur in solution it is probable that no membrane could possibly exist which would be capable of holding them back, since the membrane must itself have a molecular structure. The carbonate ions must be very much larger than the ions of hydrogen, not only because they contain a number of atoms in combination instead of one, but because the atoms themselves are many times larger than those of hydrogen. It is, therefore, almost *a priori* certain that if a membrane is relatively impermeable the hydrogen ions will still pass through it, while the carbonate ions will be held back.

Since the hydrogen ions are by nature positively charged, the outcome of this selective diffusion through the cell membrane must evidently be to form a layer of positive electrical particles on the outside of the cell. On the inside of the cell there will be a corresponding layer of negative particles which are held in position by the attraction exerted upon them by the external positive layer. This attraction is mutual and not only causes the diffused positive ions to remain in the immediate vicinity of the membrane but limits

the number of them which can pass through the membrane, since when their concentration on the outside reaches a certain limit there will be just as many returning into the cell per unit time as leave it. Thus a definite state of equilibrium is established which involves an 'electrical double layer,' of a magnitude depending upon the exact permeability of the membrane and the internal concentration of the ionized substance. The existence of such an electrical double layer at the membrane may be said to constitute a *polarization* of the latter, this polarization being capable of variations in degree under different conditions.

It is clear that the polarization of the cell membrane just considered explains the demarcation current, even the direction of this current corresponding to that theoretically deduced. When an electrical connection is made between an injured and an uninjured portion of a nerve, this connection is virtually established across the cell membrane so that the mechanism of the membrane acts in a manner similar to an electric 'battery.' The energy of this 'battery' is derived from the compression of the ionized substance inside of the cell, and the continued flow of the demarcation current must involve a diffusion of some substance, *viz.*, hydrogen, through the cell wall. This process is similar to that which occurs in the special form of electrical 'battery' known to physical chemists as a 'concentration cell.'

The next problem which we face is that of determining the *mechanism of stimulation* of the resting cell. It is a familiar fact that an externally produced electric current or voltage provides a very ready means of stimulating nervous tissue. The great sensitivity of such tissue to electric currents is by itself almost conclusive evidence of the essentially electrical nature of the nerve process. The stimulating power of electrical currents depends, however, very radically upon the exact time relations of the current. An alternating current of the right frequency stimulates more readily than a direct current, but if the frequency is very high there may be no stimulation at all, even with very large currents. It is found experimentally that the intensity threshold for a given

nerve is proportional to the square-root of the frequency. Nernst¹ succeeded in explaining this relationship mathematically on the basis of an assumption as to the physical conditions underlying the threshold. He supposed that in order just to stimulate a nerve cell, the current acting upon the cell must polarize the cell membrane to a certain critical degree, this polarization being a natural result of a current flow, which piles one kind of ions up on one side of the membrane and draws them away from the other side. By combining this assumption with the known laws of electrical action and diffusion Nernst arrived at a law connecting the time required to stimulate with the intensity of the stimulus. Although Hill,² and others have found it necessary to complicate Nernst's original theory by further details, the quantitative success of his original hypothesis stands out as a unique achievement in the application of mathematical physics to biological phenomena.

It is evident, however, that Nernst's assumption that the physical basis of the nerve threshold is the establishment of a certain degree of polarization in the cell membrane must be modified to fit the fact that the membrane is already polarized before stimulation. It was pointed out by R. S. Lillie³ that this modification might take the form of a mere change of algebraic sign; in other words, stimulation of the nerve may require a critical depolarization of the membrane, this depolarization although definite in amount not necessarily being complete. Lillie further pointed out that this assumption is in harmony with many facts concerning conditions of stimulation of nervous tissue. It harmonizes firstly with Pflüger's law of electrical stimulation,⁴ according to which there is stimulation at a negative pole (cathode) upon closing the circuit and at the positive pole (anode) upon opening the circuit, when both of these poles are applied to the

¹ *Loc. cit.*

² Hill, A. V., 'A New Mathematical Treatment of Changes of Ionic Concentration in Muscle and Nerve Under the Action of Electric Currents, with a Theory as to their Mode of Excitation,' *J. of Physiol.*, 1910, 40, 190-225.

³ *Loc. cit.*

⁴ For a statement of Pflüger's law or laws, see Howell, *loc. cit.*, pp. 89-91.

outside of the nerve. The cathode may be regarded as spraying the nerve with electrons,¹ which are negatively charged and which consequently combine with the positive particles on the outside of the nerve, neutralizing them and thus depolarizing the membrane. The anode, on the other hand, sucks electrons away from the outside of the cell, thus increasing its coating of positive particles at this point. Facts to be considered below lead us to suppose that under these conditions the membrane will react in such a way as to compensate for this increased polarization, so that when the circuit is opened and the auxiliary polarizing force of the anode is removed a depolarizing action will occur. It is a well recognized principle that anode stimulation at the 'break' occurs less readily than cathode stimulation at the 'make.'

Stimulation of nerve by many agents other than the electric current can also be explained on the assumption that the essential condition of stimulation is a certain depolarization of the membrane. One way in which to depolarize the membrane would be to place the cell in a solution containing positive and negative ions very similar in physical character to those within the cell itself. Under these conditions there would be just as much of a tendency for positive ions to pass into the cell as to pass out, so that the production or maintenance of polarization by the mechanism of selective diffusion above described would be impossible. This explains the stimulating power of various 'electrolytes.' It also explains why these substances, including carbonic acid, eventually bring about a permanent depression of activity or 'narcosis' in the nerve.

Another method which is obvious *a priori* for stimulating a nerve is to injure or destroy the membrane, which depolarizes the latter because negative as well as positive ions are permitted to diffuse through it. So-called mechanical stimulation of the nerve is evidently of this sort, depending upon a gross maceration of the cell envelope. The action of certain organic narcotics, such as chloroform, ether, alcohol, etc.,

¹ Cf. Comstock and Troland, *loc. cit.*, pp. 24-25.

which first excite and then depress the nerve, probably depends upon a *chemical* destruction or impairment of the membrane. The stimulating effect of other conditions, such as desiccation and heat, can be explained in similar terms.¹

III. THE SPECIFIC MECHANISMS OF THE THRESHOLD IMPULSE PROPAGATION, AND OTHER NEURAL PROPERTIES

It is evident that the Nernst theory of stimulation in the modified form outlined by Lillie demands a 'negative variation' of the 'current of rest,' as empirically found, since depolarization would necessarily manifest itself in this way. It does not follow, however, from any statements made heretofore that this negative variation will be *propagated* along the cell or fiber from the point of stimulation. Lillie has pointed out that to explain propagation of the variation we must suppose not only that the polarization of the membrane depends upon its differential permeability but that its relative impermeability depends upon its degree of polarization. Polarization and permeability, in other words, are the two essential factors in the nerve process, and they are related to one another in the propagation of the nerve impulse in a manner analogous to the relation of pressure and displacement in the propagation of sound² or the relation of the electric and magnetic vectors in the propagation of light.³ These relations are all such that a change in one of the quantities always involves a change in the other, the locus of the secondary change not coinciding with or falling wholly inside of that of the primary change. This relation necessitates propagation.

It is easy to see why the degree of polarization of the nerve cell membrane should depend upon its degree of permeability, since it was from assumptions regarding the nature

¹ On the various means of exciting nervous tissue see Schäfer's 'Text-Book of Physiology,' 1900, pp. 459-468.

² See, e.g., Duff, A. W., 'A Text-Book of Physics,' 4th ed., pp. 518-519; or Poynting and Thomson, 'A Text-Book of Physics,' 1904, 2, pp. 12-14.

³ See, e.g., Houstoun, R. A., 'A Treatise on Light,' 1915, Chap. XXII. This is a mathematical exposition; a simple, qualitative treatment is difficult to find.

of this permeability that we were enabled to deduce the existence of polarization. It is not so obvious, however, why the *permeability* of the membrane should alter when some external force, such as an electric current, brings about its depolarization. A moment's consideration, however, will show that such artificially produced depolarization should have some effect upon the constitution of the membrane. When the polarization is present the substance of the membrane is subjected to electrical stresses which are represented by parallel lines of force connecting the positive charges on the outside of the membrane with the negative charges on the inside. In accordance with the general electrical theory of matter these electrical stresses will necessarily produce some distortion of the molecular or atomic structure of the membrane, which distortion will have a direction determined by the impressed electrical forces. When these forces are removed by depolarization this distortion will tend to disappear. The distortion may well be of such a character as to render the membrane less permeable than would be the case if such distortion were absent. In this event, the depolarization would have the effect of increasing the permeability.

One conception of the molecular structure of the membrane which has occurred to me, pictures the membrane molecules as being considerably longer than they are wide, with opposite electrical charges on either side in the middle of the molecular length. The individual molecules are conceived to be rotatable, like compass needles, about their centers of mass. The electrical field produced by the polarization will then tend to dispose all of these molecules with their long axes at right angles to the field, that is parallel to the plane of the membrane, and in this position they will offer maximal obstruction to any particles tending to move perpendicular to this direction. When the depolarization field is removed, however, the molecules will tend to swing into position at right angles to the one just considered, on account of the mutual attractions and repulsions of their charges. In this position they will offer much less resistance to the passage

of particles perpendicular to the plane of the membrane. This mechanism is of course only symbolic, but illustrates the general principles which are involved.

Apart from purely physical reasoning, we have excellent biological grounds for believing that stimulation of a living cell will result in an increased permeability of its enveloping membrane. It is through modifications in the permeability of this membrane that the cell regulates the income and outgo of chemical materials. Food substances absorbed from the environment and waste products excreted must pass through the membrane, and it is to be expected that both of these transfers of substance will be increased during a state of excitation of the cell, since this latter state involves an increased chemical activity. Lillie has cited a number of cases in which an increased permeability of the cell membrane resulting from stimulation can be clearly demonstrated. The recent work of Tashiro on the liberation of carbon dioxide by stimulated nerve fibers is evidence in the same direction, and also corroborates the idea that the ions which are involved in the polarization of the nerve cell membrane are those of carbonic acid.

Tashiro¹ finds that a small amount of carbon dioxide is given off by the nerve fiber even in the resting state but that this amount is markedly increased during stimulation. This indicates that the normal permeability of the membrane is such as to permit a slight diffusion of carbonate ions and that the depolarization accompanying excitation is the result of an increased permeability to these ions rather than a decreased permeability to the positive hydrogen ions. Our initial theory regarding the cause of the polarization of the cell membrane demands that an increase in the permeability should result in a decrease in the polarization provided the permeability is already practically perfect for the positive ions. That this requirement is fulfilled is indicated not only by the slight diffusion of carbon dioxide during the resting state but also by the free permeability of the membrane at all times to water and the ions of water.

¹ Tashiro, S., 'Carbon Dioxide Production from Nerve Fibers when Resting and when Stimulated,' *Amer. J. of Physiol.*, 1913, 32, 107-136.

The facts which we have just been considering show that the reciprocal relationship between permeability and polarization is a mutual or 'symmetrical' one. In other words, these facts prove that a decrease in polarization beyond a certain critical point results in an increase in permeability. The analogy between the principles of propagation of nervous energy and those of acoustic and radiant energy is thus very close, a change in either one of the two principal variables resulting in a reverse change in the other variable. The reciprocal relationship between these two factors in the case of the nerve impulse is not, however, absolutely symmetrical. It is almost certain that any initial change, no matter how small, of the permeability will result in a reverse change of the polarization, but the fact of the threshold indicates that an alteration of the polarization does not bring about an increase in the permeability until a certain critical depolarization has been developed. Indeed certain phenomena which we shall soon consider indicate that before this critical point is reached, there is a tendency for the permeability of the membrane to decrease below normal as a result of depolarization. The polarization and the permeability of the membrane appear to enter into a system in which there is a point of unstable equilibrium.

The nature of this system can be illustrated by a mechanical analogy which is effective as a classroom demonstration. Suppose that we tip a chair gradually forward by applying a finger to the back of the chair. At first the weight of the chair resists the tipping force, but when the center of gravity passes over the very small base of support the chair parts company with the finger and falls to the floor with a crash. The tipping of the chair up to the point of unstable equilibrium represents the changes in the character of the membrane system which must be produced in order to pass the threshold, while the crashing of the chair to the floor, once the equilibrium point has been passed, represents the liberation of the internal energies of the nerve cell which constitutes the state of excitation. The degree of energy thus liberated is evidently dependent almost wholly upon the inherent

nature of the system and not upon the intensity of the stimulus or tipping force.

The laws of the nerve membrane system, formulated in more exact terms, would probably read somewhat as follows. An increase in permeability always produces a decrease in polarization. An initial decrease of polarization, however, first results in a decrease in permeability which tends to compensate for the initial change. But if the depolarization reaches a critical or threshold amount the 'sign' of the change is reversed, so that an increase in permeability results. As soon as this increase begins, the initial depolarization is further augmented by^{*} the law which makes polarization depend reciprocally upon permeability, so that the equilibrium of the nerve membrane system is completely upset, the polarization now decreasing to a minimum while the permeability increases to a maximum.

The supposition that the first reaction of the membrane to a decrease in polarization is a decrease in the permeability rather than an increase is in harmony with a variety of facts concerning the nerve function. It explains among other things DuBois-Reymond's law of electrical nerve stimulation, according to which a nerve is stimulated only by a *change* in an electrical current and not by a steady flow of electricity. The investigations of Waller,¹ Hill,² Lapicque³ and others have shown that there is a certain rate of application of an electrical voltage which stimulates the nerve with the least total expenditure of energy. The failure of a slowly applied electric voltage to stimulate—at the cathode—can be understood if the first action of the membrane is in the direction of adaptation or compensation, the mechanism of which involves a decrease of the permeability below normal; thus tending to increase the polarization above normal or to maintain it at normal in the face of an external depolarizing agency. Such an action is evidently a physical possibility if, as we have found reason above to

¹ Waller, A. D., 'The Characteristic of Nerve,' *Proc. Roy. Soc.*, 1899, **65**, 207-222.

² *Loc. cit.*

³ See Lapicque L., and Legendre, R., 'Relation entre le diamètre des fibres nerveuses et leur rapidité fonctionnelle,' *Comptes rendus*, 1913, **157**, 1163-1165.

suppose, the normal permeability does not completely interfere with the diffusion of the negative ions but simply impedes their movement to a certain degree. If the external depolarizing agency is applied very rapidly the membrane does not have time to develop its compensating reaction, so that the threshold depolarization is reached and excitation results.

We have seen that the 'break' stimulation at the anode is best explained on the assumption that the membrane tends to compensate for the excess of positive ions at the anode by decreasing its permeability at this point. This is apparently another instance of the general tendency of the membrane to adapt itself to a stimulus by permeability changes so as to maintain the resultant polarization constant. Stimulation at the anode upon interruption of the current will result only if this interruption is sufficiently quick, since if it is slow the membrane will have time to compensate again and the resultant change in the polarization will be insufficient to cause stimulation.

These views regarding the changes in the condition of the membrane at the cathode and anode respectively should lead us to look for some further specific effects of such modifications. The phenomena of 'electro-tonus'¹ are of this sort. It is to be anticipated that the stimulability, or the stimulation threshold, of the nerve will depend upon the condition of the membrane, in particular upon the dynamics of the equilibrium between its permeability and its polarization, so that a compensating change in the permeability will result in an alteration of the threshold. It is a familiar fact that the stimulation threshold decreases at a cathode while it increases at an anode, indicating in terms of our theory that decreased permeability results in increased stimulability and *vice versa*.

The above deductions are further borne out by a study of the alterations in stimulability which take place during and after any given process of excitation in the nerve fiber. It is well known that after such a fiber has once been stimulated it cannot again be set into excitation until a certain interval

¹ See Howell, *loc. cit.*, pp. 88-89.

has elapsed, this interval being called that of *refractory phase*.¹ Refractory phase is evidently represented in our physical hypotheses by the state of collapse of the membrane which results from the attainment of the threshold depolarization. If excitation consists in an increase of permeability to a maximum, then it is clear that further excitation is impossible until the original impermeability has been at least partially restored. So long as no restoration whatever has occurred the cell remains in what is known as *absolute refractory phase*.

The fact that this condition is only temporary proves that a mechanism of restoration of the normal condition of the membrane exists, this mechanism probably being identical with that which enables the membrane to react in a compensating manner to small depolarizing forces. The recovery is gradual and while it is in progress the cell is in a so-called state of *relative refractory phase*. In this condition its stimulability is depressed below normal to a degree which is greater the less the recovery which has been achieved at any instant. Since the recovery must consist essentially in a progressive decrease in the permeability of the membrane these facts evidently correspond with the view that stimulability is inversely proportional to the permeability in question or that the threshold of stimulation is directly proportional to it.

It is an empirical finding that the relative refractory phase is followed by a *phase of hyper-excitability* during which the threshold of stimulation is *lower* than normal. This effect can evidently be attributed to an 'over-shooting' of the permeability decrease which constitutes the recovery of the membrane. Such 'over-shooting,' according to our assumptions, should be accompanied by an increase in the stimulability of the nerve above that obtaining in the normal condition. The 'over-shooting' may be viewed as a delayed consequence of forces of compensation set into action by the initial operation of the stimulus.

¹ On refractory phase and the course of excitability after stimulation, in general, consult Bayliss, W., 'Principles of General Physiology,' 1915, pp. 389-390.

The above considerations are evidently in harmony with the facts which indicate that a nerve impulse set up during a state of refractory phase has a smaller amplitude or intensity than a normal impulse, while one which is generated in a phase of hyper-excitability possesses an amplitude or intensity greater than normal. The 'amplitude' of a nerve impulse must stand either for the amount of change in permeability which results from stimulation or for the amount of depolarization which is a consequence of this change. It should be clear why these amplitudes vary with the exact level of permeability which exists at the instant of stimulation. If a nerve impulse is represented as a wave of permeability change referred to normal permeability as a base line it is evident that a decreased amplitude is represented by an elevation of the troughs of the waves above the base line, whereas an increased amplitude must be referred to a depression of these troughs below this line. The 'all or none' principle, which we shall consider more specifically below, may be interpreted as to mean that the crests of all waves lie on a constant locus which represents the invariable maximum permeability of the membrane.

IV. THE ENERGETICS OF NERVE PROCESSES

It is almost a necessary consequence of the above outlined theory of the physical nature of nervous activity that such activity should involve metabolism. It seems almost inevitable that the process of restoring the nerve membrane to its rest condition after excitation should require the expenditure of new energy. This energy would naturally be obtained by the *oxidation* of some substance present in the cell. It is a fact that oxygen is required in order to maintain the nerve in a state of excitability. A nerve which is caused to function in the absence of oxygen eventually falls into a state of permanent refractory phase, exactly what would be expected if oxygen is necessary in order to rebuild the membrane.

It is a remarkable fact that although oxygen is required in the nerve function there is apparently no generation of

heat due to the activity of the nerve.¹ Very sensitive heat detecting instruments capable of recording the heat produced by the oxidation of a single molecule in a portion of space easily visible under the microscope have failed to indicate any heat production whatsoever. This fact has led some investigators to believe that the oxygen is not required for metabolic purposes but has some other function, such as one of catalysis. They do not make clear, however, why in a non-metabolic function the oxygen should require constantly to be replenished. The idea that the oxidation actually is employed in an oxidative process may possibly be reconciled with the absence of heat production in the following way. The process of excitation, according to the theory herein considered, involves a diffusion of carbonic acid through the cell membrane and this diffusion, being of the general nature of evaporation, should have a *cooling* effect upon the cell. This effect is immediately followed by the oxidative change, and the heat generated by this latter change may be only just sufficient to counteract the cooling produced by the diffusion. It would be quite reasonable to suppose that these two quantities would almost exactly neutralize each other, owing to the generally cyclic nature of the process.

The apparent indefatigability of nerve tissue is probably a consequence of the fact that only a very small amount of energy is required in the nerve function, so that the substance of the nerve cell can supply this energy by oxidation during a very long period. It is clear that the oxidation which we have assumed to occur in the rebuilding of the cell membrane will tend to compensate for the loss of carbon dioxide from the cell which occurs during excitation, so that fatigue will set in only when the fundamental oxidizable material of the cell is exhausted. In *vivo* this substance will naturally be replenished, while in *vitro* the nerve becomes unfit for experimental tests due to other causes, such as desiccation, long before its metabolic fuel is exhausted.

Some views of the nature of the nerve impulse have

¹ On these points, cf. Bayliss, *loc. cit.*, pp. 378-379 and 390-391.

apparently regarded it as a true cyclic process in the thermodynamic sense.¹ Such a process, resembling the propagation of light in free space or of sound in a perfectly elastic medium, would involve no loss or gain of energy at any point, the original energy of the stimulus simply being transmitted from one part of space to another. It is inconceivable, however, that all cases of nerve functioning should be thermodynamically cyclic. The original process of stimulation apparently does not consist simply in an absorption of the energy of the stimulus by the nerve; on the contrary, the stimulus apparently serves merely to operate a trigger which releases energies latent in the nerve itself. Moreover, if propagation depends simply on the principle that one portion of the nerve can be stimulated by the excitatory state of an adjoining portion, it is natural to suppose that this trigger process is repeated at all points in the nerve during the propagation of the impulse.

It is, of course, conceivable that the energy released at the point of stimulation is simply passed along the nerve during the propagation without involving any further expenditure or release of energy. There are certain cases of propagation, however, to which this supposition can scarcely apply. One of these is propagation through a so-called 'region of decrement' in which the amplitude of the nerve impulse suffers a progressive diminution, but one which is completely recovered from when the impulse emerges from the region in question. We must suppose that the reduction of the amplitude of the impulse in such a region involves a loss of energy, and the restoration of the impulse to its original magnitude when it passes out of a region of decrement must involve the expenditure of new energy. Conduction through synapses apparently involves processes of the same general character.

Other reasons for refusing to believe that the nerve impulse is thermodynamically cyclic lie in the metabolic character of all other vital activities and in the nature of

¹ On the nature of a thermodynamically cyclic process consult Lewis, W. C. McC., 'A System of Physical Chemistry,' 1916, Vol. 2, pp. 29 ff.

the specific physical mechanism which we now believe is involved in the nerve process. This mechanism requires a change in the structure of the physical substance of the nerve membrane, a re-arrangement of its constituent atoms or molecules, and such changes always involve a degradation of energy. Nervous tissue undoubtedly has a lower degree of metabolism than any other living tissue, but this is not equivalent to saying that its metabolism is zero.

V. THE BASIS OF THE ALL-OR-NONE PRINCIPLE

Modern studies, mainly those of Lucas and Adrian,¹ have made it quite clear that the action of the individual nerve fiber follows a principle of 'all or none.' If a nerve cell is set into excitation at all its excitation is *ipso facto* the greatest which is normally possible for it. A stimulus of the highest intensity can cause no greater response than one of threshold intensity. The experimental demonstration of the validity of this principle for the individual nerve fiber has involved work of a very intricate and ingenious kind, but on the theoretical side it requires very little effort to see that the response of nervous tissue should be of the 'all or none' type. If what the stimulus does is to upset a condition of unstable equilibrium in the nerve membrane, the response of the nerve must depend upon its own inherent nature and not upon that of the stimulus. The old 'train of gunpowder' analogy for the nerve impulse involved an 'all or none' action, and the modern substitute for this classical mechanism makes the same theoretical demands.

It is interesting to note that the 'all or none' principle as applied to nerve activity forces us to think of such activity in terms of fixed units of energy, so that we have a system somewhat resembling that necessitated by the modern quantum theory of radiation.² The nerve process is *quantal*, or to use a more biological term, it is *isobolic*. The conceptions of atomism and discontinuity seem to be creeping into every branch of scientific analysis; not only are the chemical

¹ See Lucas, *loc. cit.*

² See Comstock and Troland, *loc. cit.*, pp. 46-49 and 182-189.

elements atomic but also electricity, light, the determinants of heredity, and finally the activities of nerve and muscle.

The acceptance of the 'all or none' principle for nerve action does not, however, imply that all nerve impulses are of the same magnitude. The magnitude or amplitude of a nerve impulse depends upon the characteristics of the nerve substance in which it occurs. These characteristics differ for different nerve fibers in their normal condition and for a single fiber in various abnormal, subnormal and supernormal conditions. They are different at synapses from what they are in the non-synaptic portions of the nerve.

In general, however, variations in the *quantity of nervous energy* transmitted along a given nerve in unit time must be conceived to depend upon the number of impulses or neural quanta which pass through a cross-section of the nerve during the time in question. This number is the *nerve impulse frequency*, and there cannot be the slightest doubt that the concept of impulse frequency is an absolutely fundamental one for the theory of nerve action. It is probably as important for the understanding of such action as is that of wave-length for the understanding of radiation phenomena. However, the characteristics of a given nerve current are not completely determined by a specification of its frequency, since the amplitude, the length and the form of the individual nerve pulse are not determined by frequency, although they may serve to limit the latter.

VI. THE MECHANISM OF THE SYNAPSE

Facts summarized in a masterly way by Sherrington¹ indicate that nerve conduction through a reflex arc differs radically from conduction between two points in a single nerve fiber. A reflex arc always involves one or more *synapses* and all of the evidence points to the synapse as the locus of the factors which differentiate reflex arc conduction from simple nerve fiber conduction. Certain experiments of Lucas² provide us with facts which make it easy to construct

¹ Sherrington, C. S., 'The Integrative Action of the Nervous System,' 1911, pp. 14 ff.

² *Loc. cit.*, pp. 17-22.

a theory of the nature of the synapse. These experiments relate to the conduction of the nerve impulse through a so-called 'region of decrement.' Such a region is provided by a stretch of nerve fiber which has been narcotized, that is, which has been subjected to the action of a narcotic, e.g., alcohol. An impulse in passing through a narcotized stretch of fiber decreases progressively in amplitude, the total decrease being proportional to the length of narcotized fiber through which it has passed. If the narcosis is sufficiently deep or the length of the region sufficiently great, the reduction of the impulse amplitude may be such as completely to extinguish it. If, however, the reduction does not carry the amplitude below a certain critical or threshold magnitude the impulse, upon emerging from the narcotized stretch, regains its normal amplitude and continues as if it had not passed through the narcotized region at all.

All of the evidence at hand points to the view that the action of a narcotic on a nerve cell consists essentially in a permanent increase of the permeability of the cell membrane, a physical state resembling that of refractory phase. Narcotics are apparently membrane destroyers and the depth of the narcosis is represented physically by the extent to which the membrane has been injured or made permeable. That this is a correct picture of the state of affairs in a narcotized region is indicated by the fact that such a region is electrically negative with respect to a non-narcotized portion of the nerve. It is also shown by the fact that narcotic substances, alcohol, chloroform, ether, etc., in general increase the diffusion of materials through the cell boundaries. The exact physical basis of 'conduction with a decrement,' however, is less easy to picture. Such conduction apparently demands that the degree of response of one portion of the nerve fiber should depend upon the intensity of the stimulus supplied by an adjoining portion. In other words, in a region of decrement the self excitation of a nerve fiber does not follow the 'all or none' principle. At present I see no plausible explanation of this change in law.

It will be recalled that if a nerve is restimulated during

the relative refractory phase an impulse is generated which has an amplitude less than normal, while if it is restimulated during the phase of hyper-excitability the resulting impulse has an amplitude greater than normal. The experiments of Lucas show that the ability of the nerve impulse to pass through a region of decrement without being extinguished depends upon its initial amplitude. A normal impulse may pass successfully while a subnormal one generated during relative refractory phase may fail to pass. In another case, both normal and subnormal impulses may fail while one of supernormal amplitude generated during a phase of hyper-excitability may succeed. These facts are employed by Lucas to explain *inhibition* and *summation* on the assumption that synapses, in connection with which these two processes are most commonly found, are actually regions of decrement. A synapse, according to this view, is a naturally narcotized or auto-intoxicated portion of the nerve circuit. The so-called 'resistance' of the synapse is an expression of this condition. The 'resistance' is really a 'leakage,' but owing to the 'all or none' character of the nerve function the resistance cannot permanently lower the intensity of individual pulses but can only determine whether a pulse will pass through the synapse or not. The success or failure of a pulse in attempting to pass through a synapse will depend upon its initial amplitude and upon the depth of auto-narcosis of the synapse.

It is clear that if the individual impulses reaching a synapse are separated by distances so great that the condition of the nerve is restored to normal between each successive impulse, the frequency of the pulses can affect their ability to penetrate the synapse only by some accumulation of effects in the synapse itself. However, if the frequency is sufficiently high so that one impulse falls in the phase of hyper-excitability of the preceding impulse, then this increased frequency will aid the nerve current to pass through the synapse. A further increase in frequency, however, which causes one impulse to fall in the relative refractory phase of the preceding one, will render the nerve current

less able than normal to penetrate the synapse. In case the synapse is of such a 'resistance' that only supernormal impulses can pass through there will be a relatively narrow range of nerve frequencies which will be capable of being conducted through the nervous arc, and the law governing the relation of conductibility to frequency will be similar to that of *resonance*, since impulse frequencies both higher and lower than the available range will fail entirely. If, on the other hand, normal impulses are conducted, nerve currents of all frequencies up to a certain critical frequency will pass the synapse but above this frequency there will be a complete block.

Adrian¹ makes it clear that these principles are adequate to explain many of the facts of inhibition as well as of summation. An increase in the frequency of any impulse above a certain critical value will evidently result in the inhibition of this impulse and any process depending upon it, provided a synapse is involved in the nerve circuit. Inhibition of one nerve current by another may occur if the second current impinges upon the same synapse as the first one and is of a sufficiently high frequency. If two currents of different frequencies combine, the resultant current must have a frequency at least as high as that of the highest component, and if the synapse blocks the high frequency component it will also block the low frequency one. This explanation of inhibition is clearly in harmony with the effects produced by strychnine, rabies, tetanus toxin, calcium salts, and other similar agents upon the nervous system, if we suppose that these agents decrease the permeability of the nerve membrane below normal or act in a direction opposite to that of narcotics. Upon this assumption strychnine would tend to obliterate synapses, in the physiological sense of the term; regions of decrement would be wiped out, and consequently all nerve impulses of whatever frequency would be transmitted. Inhibitions would be converted into excitations and the slightest stimulus would set the entire nervous system into action. It will be recalled that previously we have

¹ In the final chapter of Lucas's book, already quoted.

associated hyper-excitability with a decrease in the permeability of the nerve membrane below normal. The converse fact that narcotics acting upon the nervous system as a whole tend to convert excitations into inhibitions is also clearly in harmony with the given account of the synaptic function.

It is improbable, however, that the mechanisms of summation and of inhibition proposed by Adrian and Lucas on the basis of their study of conduction through regions of decrement are the whole story. Nevertheless most of the differences between reflex arc and nerve trunk conduction can be accounted for if we suppose the synapse to have a mechanism not differing qualitatively from that of the plain nerve fiber membrane, although differing quantitatively from the latter to a very considerable degree. There are undoubtedly certain physical *constants* which determine the processes of the nerve membrane. Among these are the threshold depolarization required to stimulate, the magnitude of the excitation or maximal depolarization, the rate of recovery of the membrane, etc. At the synapse these constants appear to suffer a radical change in magnitude, of such a character that all of the processes are retarded; the latent period is much longer, as is also the refractory phase, and if we suppose the synapse to have a phase of hyper-excitability this also is probably much prolonged. By a proper choice of the values of the various membrane constants the majority of the characteristic features of synaptic functions can be explained.

The synaptic process is evidently a *membrane process*, which means that it is localized in a region of space having the general form of a thin sheet. It should be noted, however, that this is equally true of the general process of conduction in a nerve. The synaptic function is probably more complicated than that of plain conduction, since it involves the combined properties of two membranes in juxtaposition. Some of the peculiar characteristics of conduction through synapses which may not be explicable by the postulation of mere quantitative differences between the synapse and the

nerve trunk may perhaps be accounted for on the basis of quantitative *differences* between the two membrane elements in the synapse. For example, the fact that a synapse normally conducts in only one direction can be attributed to a difference between the intensities and thresholds of excitation for the two adjoining neurones, such that a more afferent neurone is able to stimulate a more efferent one but not *vice versa*. It is possible also that specially ionized substances may exist in certain synapses which introduce properties characteristic of these synapses.

VII. THE MECHANISM OF THE RECEPTOR

Our account of the physical nature of nerve stimulation, conduction, and synaptic transfer needs to be supplemented by considerations bearing on the *receptor* function. Receptors, in general, are recognized to be especially differentiated cells, often more epithelial than neural in character, which lower the threshold of a given nerve path for certain forms of stimuli while raising it for others. It is probable, moreover, that in addition to being stimulus selectors, receptors are essential to the *continued* stimulation of nervous tissue by any fundamental force. DuBois-Reymond's principle tends to make the effect due to the direct action of any force upon the nerve a merely momentary one. In spite of the phenomena of sensory adaptation, stimulation through receptors produces relatively continuous excitation of the afferent nerve path. Adaptation itself appears to be attributable mainly to fatigue of the receptor process rather than of the nerve path.

In a previous article¹ I have suggested a plausible physical account of a manner in which the *visual* receptors may be conceived to produce a continued stimulation of the optic nerve fibers. This account is based upon the empirical finding that the retina is electrically negative, rather than positive as would be expected, with respect to the cut end of the optic nerve. This negativity of the retina, which

¹ Troland, L. T., 'The Nature of the Visual Receptor Process,' *J. of the Opt. Soc. of Amer.*, 1917, 1, 9-13.

is increased by the action of light, seems to imply that the essential ionized substance of the rods and cones has a negative ion which diffuses through the enclosing membranes of the receptor cells more readily than does the positive ion, producing a state of polarization opposite in direction from that of ordinary nerve fibers. It is clear that a receptor cell thus polarized and in contact with a normal nerve fiber, would tend to depolarize the latter at the place of junction, thus setting the fiber into excitation. The excitation would probably be mutual, resulting in a reduction of the polarization both of the nerve membrane and of the receptor membrane. We have reasons for supposing that the inertia of the receptor process is much greater than that of the nerve function, so that in all probability the nerve would recover from refractory phase considerably in advance of the recuperation of the receptor cell polarization. However, when this latter recuperation has reached a certain point, a second stimulation of the nerve fiber would result and this process would be indefinitely repeated. The result would be a stream of quantal impulses sent along the optic nerve fibers, and having a frequency determined by the rate of recuperation of the receptor cell.

In the case of visual response it is easy to see how this frequency can be caused to vary as a result of variations in the stimulus. The direct effect of light upon the sensitive substance of the rods or cones is probably one of increased ionization and we should expect the rate of repolarization of the receptor cell membrane to increase with increase in concentration of the ions within the cell. The optic nerve impulse frequency would thus tend to be augmented by the action of radiation on the retina and to a degree greater the greater the intensity of radiation of any given wave-length.

It is certain that the processes by which sensory stimuli excite receptors are as varied as there are different forms of adequate stimuli. However, it is conceivable that the mode of interaction of the receptor cell and the conducting nerve fiber is always of the same general sort. It may be a general characteristic of receptor cells to have a negative polarization,

so that they tend constantly to depolarize and to excite the nerve fiber. A stimulus acting upon the receptor cell would in this case so operate as either to increase or to decrease its negative polarization. It is easy to imagine physical or chemical mechanisms through which such changes could be brought about by the action of almost any conceivable agency.

Rhythmic depolarization mechanisms of a sort similar to that above discussed may possibly be found in the central nervous system as well as in the periphery. The rhythm of the breathing center and other centers such as those determining certain types of peristaltic action, muscle tonus, etc., may be controlled by such mechanisms.

VIII. PSYCHOPHYSIOLOGICAL APPLICATIONS

The ultimate physical analysis of the nerve function must provide us, according to my view, with the fundamental materials on the physiological side for the construction of an ultimate psychophysical theory. The traditional doctrine of the interdependency of 'mind and body' teaches us that consciousness depends upon the existence and nature of central nerve processes. If we reject vitalistic fancies we must be forced eventually to describe these central processes in physical terms and thus to conceive them as certain configurations and changes in configuration of electrical particles.

Some modern thinkers, often officially catalogued as psychologists, subscribe to the view that there is no such thing as consciousness, and they of course cannot be expected to take much interest in the psychophysical problem. These same thinkers often appear to believe in the existence of a peculiar characteristic of physiological activity called 'the operation of the organism as a whole.' If, however, we define consciousness as simply *any given experience* we dispose of any difficulty about the non-existence of this entity, and the more we analyze the operations of 'organisms as a whole' the clearer it becomes that these operations are simply concatenations of many part processes. The ultimate account is one which expresses any process, no matter how compli-

cated, in terms of the operations of irreducible physical elements.

The central nerve process, which in the traditional theory acts as the determinant of consciousness, consists essentially, according to the modern idea, of *synaptic* functions. Such functions, however, apparently differ only quantitatively from those of simple nervous conduction, and if consciousness is associated with synaptic processes it probably is also correlated to some degree with the simpler processes of conduction. Both of these related functions, as we have seen, are membrane processes, and it would therefore appear that the physical correlate of consciousness is localized in some definite configuration of sheet-like regions of space. This 'region of determination of consciousness' is almost without doubt located in the association areas of the cerebral cortex in the case of the human introspective field, which is the main object of study for pure psychology.

The introspective analysis of consciousness provides us with certain psychical elements, attributes, and modes of relationship, for each of which it is desirable to find definite physiological correlates. A careful study of the implications of ordinary laboratory psychophysics—which determines the relationships between stimuli and their conscious reactions—with the theory of nerve action should ultimately enable us to work out some of these direct psychophysical correlations. Our theory of the receptor process in the case of vision suggests that nerve impulse frequency, or at any rate the magnitude of the nerve current, is the determinant of what we call sensory *intensity*. The characteristic *qualities* of different 'sensations' are correlated by the traditional doctrine of specific energies with the identity of the nerve path which is excited. Mere abstract identity, however, will scarcely suffice. We must suppose that these qualities depend upon peculiarities, either structural or functional, in the cerebral synapses which are set into operation by different afferent nerves. In another paper¹ I have suggested that many of

¹ Troland, L. T., 'A System for Explaining Affective Phenomena,' *J. of Abnorm. Psychol.*, 1920, 14, 376-387.

the facts about affection, or pleasantness and unpleasantness, can be explained on the assumption that its neural correlate lies in the *rate of change of synaptic conductance* in that particular portion of the cerebral gray matter which is responsible for the introspective consciousness at any given moment. Clearness and other fundamental characteristics of factors in consciousness will eventually find their proper correlates in the cerebral nerve process.

It is certain that the physical correlate of the simplest introspectively discriminable factor of consciousness must, from the physical point of view, be enormously complicated. A point visual sensation, for example, can scarcely be attributed to the function of any cerebral component smaller than a single synapse, and it is certain that a single synaptic mechanism involves the simultaneous coöperation of millions of physical atoms, electrons, electrical and magnetic fields, etc. The coexistence in a single moment of consciousness of a multitude of sensory elements arranged in a definite pattern must depend upon the concurrent and unified functioning of a large number of cerebral synapses. Unless we are to employ assumptions which suggest a non-physical or spiritual factor in the determination of consciousness, we must suppose that the unity of consciousness depends upon some sort of unity in the total nerve process upon which consciousness depends.

I am attempting to work out plausible solutions for some of these fundamental psychophysical problems in connection with a general metaphysical theory which I have called 'Paraphysical Monism.'¹ This doctrine provides us with an explanation of the facts of psychophysical parallelism which eliminates the fundamental dualism of the Leibnitzian preëstablished harmony, permitting us to combine the facts of physics and psychology into a unified system. Psychology needs all of the stimulus which it can derive from the advances of physical and physiological science. Indeed, this need is so dire as almost to warrant the suicidal promulgations of those 'psychologists' who call themselves

¹ Troland, L. T., 'Paraphysical Monism,' *Philos. Rev.*, 1918, 27, 39-62.

'behaviorists.' The psychology of the soul is dead, and that of consciousness is suffering murderous attacks. Whatever we may think of the former, the latter is assuredly worth saving, and it is my impression that the data provided by modern nerve physiology will provide us with means for resuscitating the true science of physiological psychology as it was conceived by Fechner, Müller, Helmholtz, and other pioneers.

THEORIES OF THE WILL AND KINÆSTHETIC SENSATIONS

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Theories of the will in psychology owe their origin to the development of ethical views among the early Greeks. These theories, together with those held by the early Church Fathers and the Scholastics, may be classified as intellectual and absolute. Both of these groups made will a faculty of the soul. The intellectual theories derived their name from the importance which they ascribe to the faculty of reason as a constituent of willing; the absolute theories made all other faculties of the soul subordinate to the will. In the Aristotelian view the will consisted of a 'desire' to which a 'goal' or an 'end' was supplied by the reason. Desire was analyzed as a persistent state of unrest or striving and was the essential active or dynamic feature of mental life. During the middle ages theories of the will were concerned largely with the problem of determinism versus freedom, hence the relative importance of the two faculties, the intellect and the will, as agents in controlling human behavior, was a subject of paramount importance.

As a consequence of empirical and inductive methods, we find in England from the time of Hobbes to Hume the development of a new type of theory, the emotional theory. Hume regarded the feelings as essential constituents of every volitional process. Locke had previously held that disquietude or uneasiness constituted the origin and the dynamic feature of volition, a view which in its essence was but a rehabilitation of Aristotle's potential desire. On the continent from Descartes to Herbart the tendency was gradually becoming definitized of conceiving the will as the active side of mental life in general, or as a general striving tendency.

Up to the time of more modern psychology, then, there

were in general three views of the will. In a broad sense of the term the will included all mental activity as such, an activity characterized as a potential desire or as a state of unrest. This tendency culminated in a definitized theory of conation. Secondly there was a voluntaristic tendency to employ the term will itself to mean this active feature of mental life or the source and cause of action. Thirdly there was a tendency to bring the will into intimate relations with the feelings where the feelings were regarded as essential constituents of volitional processes.

Modern theories may be classified according to the feature most characteristic of each, namely its emphasis upon the reductivity or the non-reductivity of will to a complex grouping or mode of functioning of simpler constituents. Those theories which reduce will to a peculiar order of sequence of sensations, images and affections and which do not emphasize the elementary nature of any one constituent we may call the *totally reductive*. On the other hand those theories which admit the existence of an elementary mental content—an elementary and unique volitional process—may be called *non-reductive*. In this latter group the will has an elementary content which is not necessarily independent, functionally, from other contents. Intermediate between these two groups of theories is another which we may call the *partially reductive*. Here the will is reduced partly to the functioning of the traditional elements of consciousness and partly to a unique elemental content. The latter might be said to constitute a structural and functional criterion or an essential conscious concomitant of the volitional consciousness. This group may be subdivided thus: (1) those theories which posit a conative element; (2) those theories which posit an intrinsically active ego; (3) those which regard the feelings as the essential constituents of will; (4) those which ascribe to mental processes a force or general innervation mechanism. A final group of theories may be called motor or behavioristic owing to the fact that emphasis in them is laid upon the principle of stimulus and response. Here the will, reduced to its simplest terms, becomes a system of coördinated reflexes or motor responses and the innervation mechanisms are not mental but physiological.

Non-reductive Theories.—Lotze¹ conceived the will to be an unanalyzable psychic process which functioned chiefly in choice and resolve. Since it was not constantly functioning as a datum of consciousness it was relegated to the domain of the subconscious where it found a resting place when not actually in operation. In the more recent literature Ach² and Michotte³ might be mentioned among those who, in consequence of their failure to analyze the volitional process experimentally and in consequence of finding a ‘feeling of mental activity’ in ‘genuine’ volitional acts, make a certain part of the volitional consciousness, at least, elemental and non-sensory. James’⁴ most often quoted ‘fiat’ consciousness was a subjective experience *sui-generis* which could be designated but not defined.

Partially Reductive Theories.—Herbart’s⁵ theory of the will is an early example of the conative theory. Here the will in its elemental form was to be found in the striving of ideas for existence in consciousness or for the possession of the conscious level. This striving process began in the realm of the unconscious. Volition consisted first of *desire*, a product of resistance between striving ideas and secondly in the opposition between groups of associated ideas (goals of purposes). Lipps⁶ assumed a striving process not only in ideas but in feelings and sensations as well. Both affective processes and feelings of activity were essential constituents of willing and of the volitional consciousness. The conationists, among whom may be mentioned Stout,⁷ especially, ascribe to each conscious state an inherent tendency to pass beyond itself into another conscious state, a striving process which is directly labelled conation and which, in itself, is present to consciousness.

Writing from the point of view of a self psychology Calkins described the content of willing as an active ‘consciousness of

¹ ‘Medizinische Psychologie,’ Leipzig, 1852.

² ‘Ueber den Willensakt und das Temperament,’ Leipzig, 1910.

³ ‘Etude expérimentale sur le choix volontaire et ses antécédents immédiats,’ *Arch. de psychol.*, 10, 1910, 113–321.

⁴ ‘Principles of Psychology,’ 1890, Vol. II.

⁵ ‘Lehrbuch der Psychologie,’ Leipzig, 1850.

⁶ ‘Von Fühlen, Wollen und Denken,’ Leipzig, 1902.

⁷ ‘A Manual of Psychology,’ London, 1913.

my active connection with other selves or with other things' ('First Book in Psychology,' 3d rev. ed., p. 226). The volitional consciousness is said to involve the essential non-sensory factor of the 'self-as-willing.' Ach and Michotte found an immediate and unanalyzable consciousness of the self or an intrinsically active ego in all genuine volitional acts. Meumann¹ assumed that the process of 'accepting' a goal idea, in a volitional act, involved an immediate consciousness of the self. Both partially reductive and totally reductive tendencies can be found in the analyses of volition which have been made by these latter writers.

The emotional theory of the will may be illustrated by reference to Bain² and Wundt.³ Bain defined the will as all mental and physical activities insofar as they were guided or impelled by the feelings of pleasure or pain. Wundt's theory (which is voluntaristic as well as emotional) makes will the original energy of consciousness, the first and primary form of which is a simple impulse motivated by pleasure or pain. When an organism experiences a simple sensation there arises a feeling process which develops to a maximal state of intensity beyond which it overflows into movement. Such a sensation-feeling-action series of experiences and events is called a simple or primary act of will. Feeling processes, therefore, possess an innate capacity toward willing. This is either a capacity to arouse physical movements or to initiate into consciousness other mental processes. In more complicated forms of will the feelings or emotions may be observed to increase gradually in their intensity, beginning with pleasantness or unpleasantness, eventually developing into strain or excitement. These feeling states fuse into a 'total feeling of activity' which is an essential conscious concomitant of complex or secondary acts of will. In this category are found such acts as choosing and performing difficult tasks. Secondary volitional acts may be motivated by ideas which are associated with the feelings.

As an example of a 'force' theory may be cited Fouillée⁴

¹ 'Intelligenz und Wille,' Leipzig, 1913.

² 'The Emotions and the Will,' London, 1899.

³ 'Grundzüge der Physiologische Psychologie,' Leipzig, 1903.

⁴ 'L'évolutionisme des idées-forces,' Paris, 1893.

for whom sensations and feelings are at the same time conscious states and mental forces according to the viewpoint taken in regarding such mental processes as contents or as acts.

Totally Reductive Theories.—Münsterberg¹ held that the will as a datum of consciousness was a goal-idea which had come to be associated with other ideas or with muscular movements. This goal-idea involved the anticipation of an end. In other words it is a mental process of sensory origin having to do with preparatory motor adjustments. Ebbinghaus² in like manner held that volition consisted in the capacity to foresee the end of action by associating an image with an act in such fashion that the image would function as the stimulus for the subsequent act. In the views of Ach³ and Meumann⁴ we might have found totally reductive theories had it not been for the fact that both ultimately drag in a non-sensory experience pertaining to the self and feelings of activity. Meumann described the will as a selective process brought about by means of 'accepted' goal ideas, while in a similar fashion Ach found the clue to a volitional act in the acceptance of an *Aufgabe*. The capacity of goal-ideas to so control subsequent mental processes depended upon the previous forming of associations between the foresight of an end and the act which attained that end.

Behavioristic Theories.—The modern trend of descriptions of the will is obviously behavioristic, where the emphasis is laid upon the coördinated responses of the organism to its environment and not upon the mental contents as such. But owing to the lack of experimental evidence accurate accounts of the volitional process cannot be presented. According to Ribot⁵ the will is to be regarded as the sum total of the organism's responses to environment. All mental processes tend to express themselves in some form of overt action and would succeed in doing so were it not for processes of inhibition. The continuity of mental states can be expressed only in terms of the continuity of these organized motor responses.

¹ 'Die Willenshandlung,' Freiburg, 1913.

² 'Grundzüge der Psychologie,' Leipzig, 1911.

³ *Loc. cit.*

⁴ *Loc. cit.*

⁵ 'The Diseases of the Will' (trans.), Chicago, 1903.

Notwithstanding the numerous descriptions and interpretations of the will which have appeared in the literature we find little genuine progress in ascertaining the exact characteristics of the volitional consciousness. It is evident, however, that it cannot be described adequately in terms of structural contents alone. Functionally, two distinct problems are involved, namely those of the will in a broader and in a narrower sense. In the broader sense the problem of the will should be identified with the problem of the general sequence of mental processes. Such discussions seek to answer the question, how may the sequence of mental processes be envisaged in mental terms? Or stating the problem in objective terms: how may the continuity of the organism's responses to environment be best described? In the narrower sense the will should be identified with the problem of a particular portion or order of sequence where the question is asked how may one group of mental processes exert an apparent directing influence over subsequent mental processes? Stated in objective terms: how may one response lead inevitably to the making of a subsequent response?

Theories which have been formulated from a subjective point of view have reduced the will, in the broader sense, to a potential desire (Aristotle), to a state of uneasiness (Locke), to a striving process (Herbart, Lipps), to a conative tendency (Stout, Baldwin and others) to an intrinsically active ego (Calkins, etc.), to innervating properties of the feelings or emotions (Bain, Wundt) and to an alleged dynamic force (Fouillée). Other writers have concerned themselves with the general problem of sequence but from an objective point of view; hence the will has become the sum total of the organism's motor responses (Ribot and others).

Still others who have faced the same problem and who have borne in mind both its structural and functional aspects have failed to find any structural clue to the general problem of sequence, hence for them the problem becomes one of a unique or particular order of sequence. Here, again, failing to find elementary structural clues they have formulated theories of a totally reductive character. In such theories the im-

portant rôle is assigned to a goal-idea or *Aufgabe* which conditions the sequence of mental processes by means of productive or selective influences. On the other hand there have been many attempts to state clearly the problem both in its broader and narrower aspects. For example, the will in its narrower sense (volition proper) was envisaged by Aristotle as a rational desire; by Hume, Bain and Wundt as a highly organized sequence of potential emotional processes associated with ideas; by the conationists as a highly organized conative system the distinctive feature of which was the foresight of an end. Another view involves an assertive attitude of the self (Calkins). The problems have been the same throughout all these discussions; but how different have been the solutions!

The confusion found in these descriptions can be traced obviously to widely different points of view. Advocates of partially reductive theories have been obliged to appeal either to a volitional constituent in the feelings, to an alleged conative element, to an intrinsically active ego or to forces inherent in sensation and affection in order to account for the general conscious continuum in purely subjective factors while adhering at the same time to an atomistic conception of mind. It is the problem of getting elementary states of consciousness back into a working, active system again after they have been assigned the rôle of units or 'atoms.' It is the problem of making a river out of a succession of barrels in the stream bed. Witness the attempts of those writers who adhere to an atomistic and structural conception of mind but who have failed to discover any elemental conscious experience whose constant presence in mental life will explain the continuity of conscious states. Such writers (James,¹ Brentano,² Witasek³) have resorted to other factors such as to a differentiation between transitive and substantive states or between act and content. From a more objective point of view the recent motor movement in psychology seems to be based essentially upon an attempt to solve the general problem of sequence and unbroken continuum.

¹ *Loc. cit.*

² 'Psychologie vom empirischen Standpunkte,' 1874.

³ 'Grundlinien der Psychologie,' 1908.

As for the narrower problem—the determination of subsequent processes by an antecedent process—one finds the same divergence in points of view and in results. The issue has been definitely sharpened by positing the existence of a determining tendency or directing of the course of the stream of consciousness. But this determining tendency may be either a driving, *a vis a tergo* exerted by the *Aufgabe* (Ach) or a leading—an attracting—by goal ideas (Meumann). Auxiliary principles such as associative tendencies, perseveration tendencies and constellations have been appealed to in an endeavor to formulate the problem and its solution more clearly. But the traditional principles of association have borne the burden throughout all these more recent discussions. The objective or behavioristic attack upon this same narrower problem includes the reflex-arc concept (Dewey)¹ and the principle of ideo-motor action.

The solution of these problems has been delayed, also, because of the very meager introspective analyses which have so far been made under experimentally controlled conditions. It is extremely doubtful whether a genuinely vigorous volitional act has ever, in the past, been subjected to adequate introspection.

It seems to the writer that insofar as the partially reductive theories have been based upon introspective evidence, the trouble has been in a failure to reduce conation, striving process, feelings of activity, etc., to a common process. We have every reason to believe that many of Wundt's 'feelings,' for example, are forms of kinæsthetic sensations. Is it not quite probable that what the conationists have called the immediate conative experience is kinæsthetic sensation? The writer is firmly convinced that the 'feeling of mental activity' described by Ach and Michotte is a complex of kinæsthetic sensations. Moreover is it not also possible that Meumann's consciousness of the self in the acceptance of a task or that Professor Calkins's intrinsically active ego are interpretations unwittingly based upon an immediately experienced but complex and diffuse kinæsthetic background and nothing else? Within the last

¹ 'The Reflex Arc Concept in Psychology,' PSYCHOL. REV., 1896, 3, p. 357.

few years there have appeared several elaborate introspective descriptions¹ of various conscious processes but in none of these do we find the slightest hint of such elements. Kinaesthetic sensations are with us always in mental life. Recent introspective works and more especially those of Fernberger and the writer show the importance of such processes. In fact, as the writer has shown in an introspective study of choosing,² kinaesthetic processes are essential and as a type the only essential form of elemental conscious process in the act of choosing.

It does not seem unwarranted, therefore, to conclude that the extreme variations in past descriptions of the will consciousness both in its broader and narrower aspects have been due to various interpretations of a consciousness which is so largely made up of kinaesthetic sensations. From these experiences we get our notions of striving, strain, activity, force, conation and the like. It may be open to question, also, whether the Freudian wish and its various cousins are not veiled and unconscious interpretations unwittingly based upon a consciousness of kinaesthetic strain.

To sum up, theories of the will in the history of psychology represent successive attempts to describe the conscious continuum as a whole and to describe the process of control in any given portion of the conscious continuum. The chief cause for the great variability of these descriptions lies in a further attempt to find evidence of this continuity in some unique mental process. Where such an elemental process has been found lacking we have been obliged to resort to the principle of act and content. Various points of view have added to the confusion. And in modern psychology, inadequate introspective data has led to inadequate interpretation. The unique mental process, we believe, is nothing more than kinaesthetic sensation.

¹ E. L. Woods, 'An Experimental Analysis of the Process of Recognizing,' *Amer. J. of Psychol.*, 1915, 26, 313-387. S. C. Fisher, 'The Process of Generalizing; and its Product, the General Concept,' *Psychol. Mon.*, 1916, 21, No. 2 (Whole No. 90). S. W. Fernberger, 'An Introspective Analysis of the Process of Comparing,' *Psychol. Mon.*, 1919, 26, No. 6 (Whole No. 117).

² R. H. Wheeler, 'An Experimental Investigation of the Process of Choosing,' University of Oregon Publications, 1920, Vol. 1, No. 2.

This compels us to settle upon a point of view. It shows us the futility of searching for introspective evidence of continuity and places us in the position of the other sciences where we rightly should be—the position of finding continuity in data treated from an objective point of view. We should look for the solution of the problem, therefore, in behavioristic principles. The cry at present is, in some circles, to do away with introspection. But in the other sciences observations are made *via* the senses. Why can we not observe our own behavior in the same way? Introspection as sensory evidence of our own behavior ought to be as valid as sensory observation of any movement external to our bodies. Let the 'feel' of a response be as ample evidence of the existence of that response as the 'sight' of it in another person or an animal. To be sure introspective evidence should be verified wherever possible both by objective instruments and by similar reports from large numbers of observers. Our view is that in attempting to solve psychological problems in the future,—problems which were formally considered purely subjective—we are warranted in drawing behavioristic interpretations, in part at least, from introspective data.

A PURSUIT PENDULUM¹

BY WALTER R. MILES

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One of the measurements used at the Nutrition Laboratory on the aviation candidates in the spring of 1917 was to record the adequacy of ocular-pursuit movements in following the swing of a pendulum. The subject was seated at a head-rest with the left eye covered. A polished metal bead suspended by an invisible cord was arranged to swing through a visual angle of about 40° . The pendulum made a double swing in 2 seconds. Its release was synchronous with exposure of the eye to the recording beam of light, after the manner of Dodge's photographic technique.² The repeated instruction was to watch the bead intently every moment of its swing. Six or more successive trials by a subject were photographed side by side on one plate. These records do not easily provide an exact quantitative score for accuracy of pursuit. However, it is convenient to rank these photographic records showing the reaction time occurring at the start of the pendulum's swing, together with the number and size of abrupt horizontal movements by which the subject supplements his inadequate pursuit, into five grades or groups of excellence. Such grouping gave a positive correlation of 0.40 with the subsequent progress of these men in learning to fly.³

¹ In abbreviated form this paper was read before the American Psychological Association, Cambridge, December 30, 1919.

² Diefendorf and Dodge, *Brain*, 1908, 31, pp. 451-489. See Plate II for illustrative records showing fully the characteristics of this type of eye-movements. For a description of the eye-movement recording apparatus as used on the aviation candidates, see Benedict, Miles, Roth, and Smith, 'Human Vitality and Efficiency under Prolonged Restricted Diet,' *Carnegie Inst. Wash. Pub. No. 280*, 1919, pp. 159 ff. and pp. 184 ff.

³ Our subjects, the first groups of candidates to attend the Aviation Ground School of the Massachusetts Institute of Technology, were a very superior lot of men. Nearly all graduates of our best universities, these men had been prominent in athletics and many of them on their own initiative and at their own expense had taken some

At the time this result was found hardly any single test indicated a higher correlation with flying. Officials advised, however, that the ocular-pursuit measurement, as carried out photographically, was too complex for any general use in the preliminary selection of candidates for pilot training.

These details have been recited as they account for the simplicity of the device described below. The pursuit pendulum was an effort to meet a definite situation. Care was exercised to exclude all electrical and photographic or other graphic features, to make the apparatus its own gravity-operated chronometer and such that it could be used nearly anywhere and would give an immediate quantitative score for the accuracy of the eye-hand coördination in pursuit movement. Although an opportunity never came after the development of the test to try it on a group of aviators or men who were in this training, the possible general usefulness of the measurement to other laboratory workers and in industry may warrant the description of the pursuit pendulum, together with illustrative data for initial performance, improvement with practice, and changes in efficiency, *e.g.*, as produced by a superimposed nutritional factor such as alcohol.

From a suitable wall bracket a pendulum carrying a reservoir is arranged to swing over a sink or table, a small stream of water flowing from the lower extremity as the pendulum swings. The individual under test, seated before the sink, attempts to catch the water in a cup of limited diameter. A separate cup is used for each double swing and the volume of liquid collected represents quantitatively the adequacy of pursuit.

The bracket, *A* (see Fig. 1), extends from the wall about 45 cm. and is fairly rigid. The pendulum, *B*, 140 cm. long, training in aviation. They were keenly interested in aviation problems and coöperated whole-heartedly, as did also the officials at the ground school. Although about 65 men were measured, the government found it imperative to send many of these to Europe immediately upon their having finished at the ground school, and they therefore received the flying training abroad. Most energetic efforts were made by Professor E. L. Thorndike to secure the flying scores for these men on whom Drs. H. E. Burtt, L. T. Troland, and myself had worked. Scores for 26 were finally obtained and it is for these that the correlation mentioned was found.

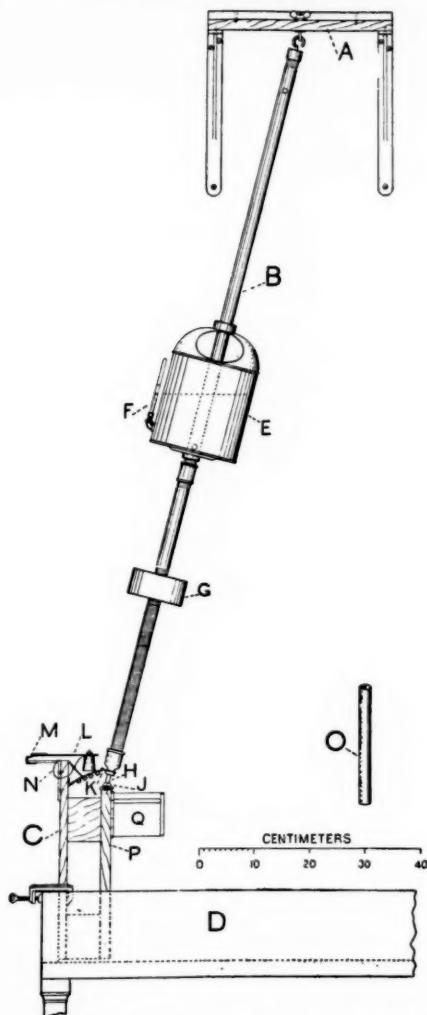


FIG. 1. Diagram of the pursuit pendulum. *A*, wall bracket; *B*, pendulum carrying reservoir, *E*. Gauge, *F*, determines volume of liquid in reservoir. *G*, adjustable weight regulating pendulum's period. *C*, wooden frame clamped to sink, *D*. Nozzle, *H*, of pendulum held by catch, *K*, against rubber tubing, *J*, until released by fall of hammer, *L*, hinged at *M*. Short section of chain, *N*, determines lift of hammer. *O*, cup of limited diameter, in which the expelled liquid is to be collected by the subject under test. *P*, position at which cup, *O*, is held at start. *Q*, short-stop for ending the catch.

is suspended by two screw eyes. Its shaft is continuous through the reservoir and is very stiff, being made of sections of galvanized-iron pipe (regular $\frac{1}{2}$ -inch inside diameter). The reservoir, *E*, a 1-gallon galvanized-iron oil can, surrounds the shaft and is firmly secured and made leak-tight by the use of a "railing flange" soldered to its bottom. As the reservoir is located about midway the length of the pendulum, the head of water changes but little with the decreasing level in the can. An adjustable weight, *G*, of about 4 kilograms allows for regulation of the pendulum's period and makes the position of the center of mass much less dependent upon the exact amount of liquid in the reservoir. Openings are arranged in the pipe shaft on a level with the floor of the can and air vents are placed above. The water flows very freely from the reservoir, and at the lower end of the shaft is reduced to a stream 3 mm. in diameter by the nozzle, *H*.

A simple arrangement for retaining and releasing the pendulum is shown in Fig. 1 and separately illustrated by a top view in Fig. 2. The wooden frame, *C*, is clamped to one end of the sink, *D*, at such a height that when the orifice, *H*, is slipped up on a cushion, made of a short horizontal section of rubber tubing, *J*, a closure is made which is practically leak-tight. A catch at *K* retains the pendulum in this position until the fall of the rubber-headed hammer, *L*, hinged at *M*. The hammer is lifted by the operator and held in a nearly upright position, determined by a short section of chain (see *N*, Fig. 1). It is released on verbal signal from the subject and requires 0.3 second to fall and start the pendulum. This method of release corresponds to common industrial operation and the reactor, especially a subject without psychological training, likes it better than having the start occur at some arbitrary and more or less unexpected time beyond his control.

The cups in which the subject is to catch the expelled liquid (see *O*, Fig. 1) are made of thin-walled brass tubing, 19 mm. (regular $\frac{3}{4}$ -inch tube) inside diameter and nearly 22 cm. long. At the start a cup is held at position *P*, against the wooden frame, nearly vertical from and about 2 cm. lower

than the orifice, *H*. No water leaks into the cup and it is possible to begin the hand movement almost in register with the pendulum. While the subject follows the pendulum to the right, the operator turns the short-stop, *Q*, from position 1 into position 2. (See Fig. 2.) This metal screen stops the return movement of the cup at a distance of 2 cm. in front of position *P* and thus gives the operator a little space within which to catch the pendulum and replace it on *J* without spilling liquid into the cup, as otherwise an error would be introduced in the result.¹

With two liters of water in the reservoir the period of the pendulum for a double swing is just 2 seconds. Naturally this time will increase somewhat as water is lost and the center of gravity lowered. Practically, the change is of no consequence to the test, as we find that with two liters of water 20 v. d. require 40 seconds, while with one liter 40.3 seconds are required, and when the reservoir and shaft are empty 40.9 seconds are required. Thus, for testing purposes the period of swing may be regarded as independent of the

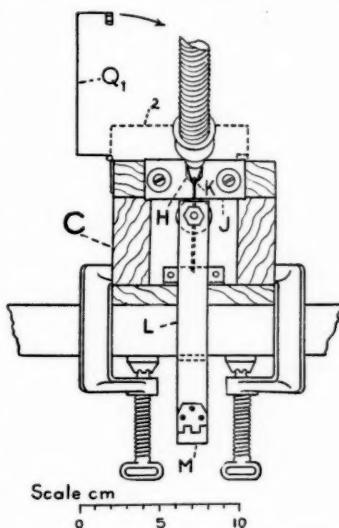


FIG. 2. Top view of the arrangement for retaining and releasing the pendulum. *H*, pendulum nozzle pressed by the rubber tube, *J*, to form leak-tight closure; *K*, hook by which pendulum is held in position until *K* is depressed by the hammer, *L*, which is hinged at *M*; short-stop, *Q*, at an appropriate time is turned into position 2 in order to cut the return pursuit slightly short and allow space in which the experimenter may catch the pendulum.

¹Another source of error must be guarded against with the coöperation of the subject. He should be cautioned not to slip the cup up over the nozzle of the pendulum or, indeed, to bump the cup against the nozzle and thus interfere with its motion. The stream of liquid does not spray out and there is no advantage, from this standpoint, in having the mouth of the cup very near the pendulum. This requirement not to touch the pendulum with the cup is a part of the coöordination, but unfortunately does not show in the objective results.

amount of liquid in the tank. The amount of head of the liquid and the size of the orifice were arranged with the idea that 50 c.c. should be the possible catch per double swing. With 2 liters in the reservoir at the start, it is found that at the first double swing the subject can catch, possibly, 50.4 c.c. and at the tenth succeeding catch 49.7 c.c. For eight successive trials the amount delivered is thus within 1 per cent. of 50 c.c. It has seemed satisfactory to replenish the water every five or ten trials. If the subject is catching nearly all the liquid expelled, the opening in the cup should be reduced. A gauge, *F* (Fig. 1), on the side of the tank makes it a simple matter, when introducing water at the opening in the top of the reservoir, to determine that the volume of water shall be up to 2 liters. During the swing the orifice of the pendulum, as used in the collection of the data presented below, moved a horizontal distance to the right of 70 cm. This is a fairly large excursion, but most adults can follow the movement without swaying of the body, if they so desire.

More complex arrangements of such pursuit apparatus naturally suggested themselves, for example, the pendulum might be made the long arm of a siphon. An orifice, not a part of a pendulum, might be carried on a belt and given a complicated series of movements, prolonging the pursuit and requiring coördination for forward and backward as well as for lateral displacements.¹ After the experience with the ocular-pursuit measurement it was assumed, however, that in trying to contribute to the problem of selecting aviation pilot material the simpler the test apparatus the more serviceable it might possibly become. Therefore this model was made independent of electrical features, did not require running water or a sink, could be filled by hand from a pitcher and could be arranged over a table or inclined trough, as the operator's conveniences might permit.²

¹ In a personal communication Professor Carl E. Seashore informs me that, after trying the original test at the Nutrition Laboratory, he has arranged a very successful combination for testing motor ability to perform circular pursuit movements, by using a phonograph motor, a time-interrupted circuit, and an electric counter.

² A criticism which may be raised against the quantitative score which the apparatus makes possible is that this score is not a sufficiently graduated result. Prac-

In practice successive catches can follow each other rather rapidly, their speed being largely determined by the quickness of the subject's motions in replacing and taking up the cups and the promptness of his verbal signals for release of the pendulum. Twenty-five trials are easily made in five minutes. The 25 cups stand in order, as at *R* in Fig. 3, being conveniently held in a box frame, *S*. Each fifth cup has a black band near the top serving in the test as a signal to the operator to replenish the water in the tank. If there is no time immediately after the test to measure the results, the cover, *V*, is placed over the open ends of the cups, the name, date and hour are noted at *U*, and the box is set aside.

In measuring the results it is tedious to empty each cup separately into a small graduate and so determine the volume of liquid. Since the cups are all of the same inside diameter (as nearly so as brass tubing is commercially made) and all have the same inside depth, a graduated scale, *W*, cut from thin aluminum sheet attached to a cork float can be introduced into the mouth of each cup as these are held conveniently side by side in the box frame, *S*, and the volume of liquid can thus be very quickly determined for the successive catches. After the catches have been individually measured, provided that such analytical data are desired for securing a measure of variability, the frame, *S*, is grasped in such a way that the rubber tube, *T*, attached to the hinged door on the front, presses against all 25 cups so that their contents may be emptied and drained at once into the inclined V-shaped trough, *X*, and so into the large graduate, *Y*. The total score is in this way very readily secured.

If a good subject reaches such a degree of skill that, for example, he regularly catches more than 80 or 90 per cent.

tically, it makes no difference whether the pursuit is so accurate that the stream of water goes in at the center of the opening in the cup or over at one side, just so long as the whole stream is collected. Since the edge of the cup is sharp, tapered from the outside, if the stream strikes here it will be divided, part collected and part lost. With a slower-moving pendulum, a somewhat larger orifice, and a cup with the mouth the same size as the orifice, probably an arrangement could be made so that the subject could always catch a part of the liquid and thus small inaccuracies of pursuit would more properly be represented in the result.

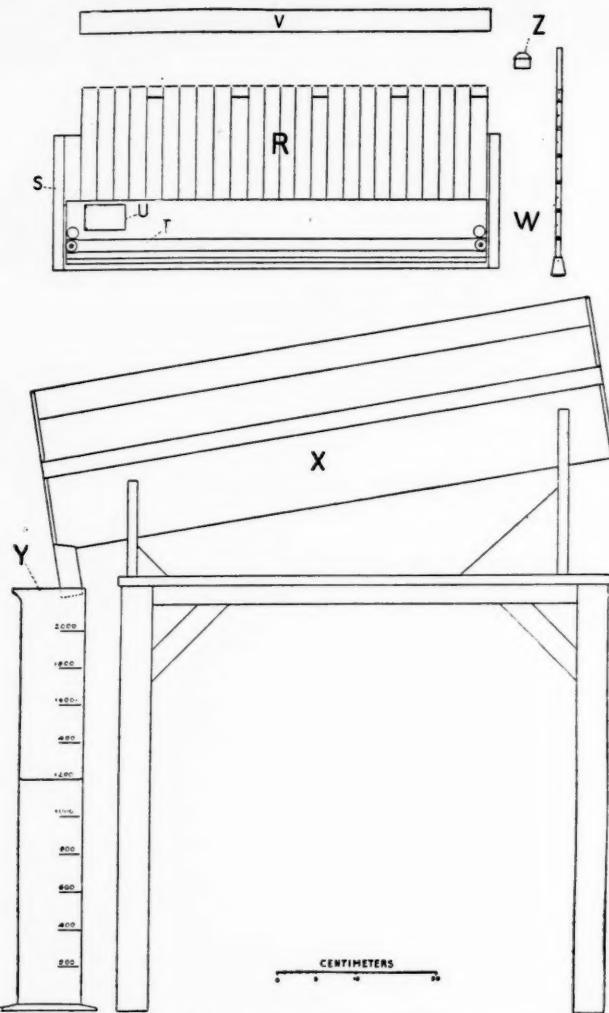


FIG. 3. Arrangement of the cups in a way convenient for measuring the quantity of liquid, by simple accessory apparatus. *R*, bank of cups in carrying frame, *S*; *V*, cover for cups; *U*, pad for noting name, date, and hour; *T*, rubber tube attached to hinged door of frame, *S*, which is pressed against cups in emptying; *W*, measuring float graduated in c.c.; *X* and *Y*, inclined trough and large graduate for receiving the contents of a whole bank of cups emptied at once; *Z*, collar to reduce the opening at the mouth of the cups, for especially expert subjects.

of the possible catch, the task may of course be made more difficult by decreasing the effective opening in the cups. A collar, Z, can be slipped into and withdrawn from each cup by the subject as he uses them in turn and thus the opening may be reduced to 10 mm. or to whatever size is deemed desirable to make the task satisfactorily difficult.

It is probable that any investigator who arranges such an apparatus as is here described will not make it an exact duplicate. Nevertheless illustrative data are of value in supplementing the description of the apparatus, as they give an idea of the type of results that may be expected from its use. In December, 1918, and January, 1919, considerable data for this test were obtained on a group of staff members of the Nutrition Laboratory, including ten women and eight men.¹ The pursuit test was given on 35 days, usually successive except for Sundays, and the amount of practice was 20 catches per day. At that time the equipment of cups consisted of two banks of ten each. It was hardly feasible that each individual should be tested at exactly the same time on each day, but care was taken not to measure subjects when they were fatigued or otherwise indisposed.²

The average results for a group of 18 adults are shown graphically in Fig. 4. Each plotted point on the curves represents 360 catches, *i.e.*, 20 catches by each of 18 subjects. Each of the two groups of ten catches made by a subject on a single day was dealt with separately when obtaining the average and standard deviation. This was done to show the progress made during the day. As might be expected, the second ten catches almost invariably averaged 1 or 2 c.c. higher than the first ten and the variability was usually smaller. For this brief paper we have averaged the two means

¹ The collection of these data, including its tabulation and elaboration, was successfully accomplished by an assistant, Mr. E. S. Mills, whose care and cooperation are gratefully acknowledged.

² In this early practice experiment it was thought that the subject should execute the pursuit by an arm movement not supplemented by a body movement. Therefore two rods were arranged to extend from the sink and to be brought in contact with the individual on both sides, somewhat above the waist. These rods, while not hindering the trunk from twisting, obviated the subject's swaying from side to side. Probably this restriction is unnecessary. It has not been used in later measurements.

and the two coefficients of variability secured for each of the 18 individuals on each day and have employed these 18 quantities to obtain the average represented by each plotted point on the curves shown in Fig. 4.

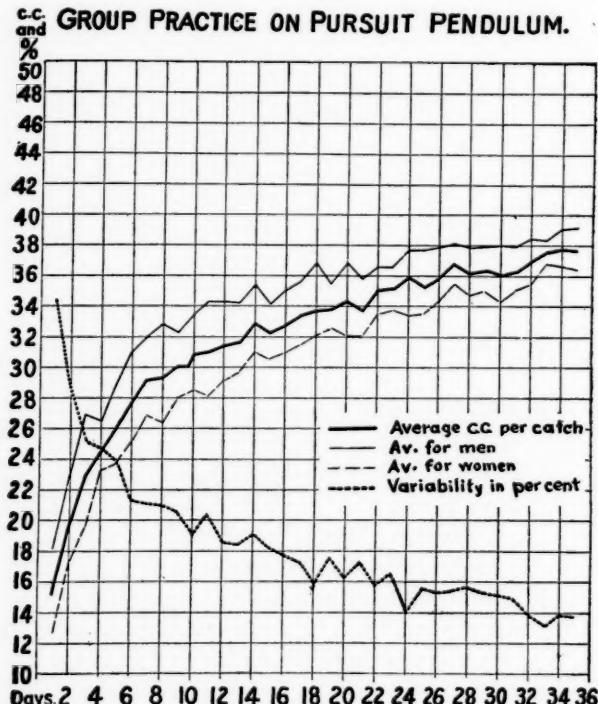


FIG. 4. Curves showing average results for ten women and eight men tested on 35 days with 20 catches per day practice.

The heavy broken line in the figure indicates the coefficient of variability (standard deviation divided by mean) in terms of per cent. The heavy solid line gives the average catch in cubic centimeters per day. On the first day the individual averages ranged from 8 to 29 c.c. per catch with a grand average of 15 c.c., which represents 30 per cent. of the possible catch. First trials by a number of other adults confirm this figure as about what may be expected for an initial per-

formance, when the subject seriously tries the test and consistently makes 20 or 25 catches. The curve showing the average catch per day rises rapidly on successive days to 20, 23, 25, 26, 28, and, on the tenth day, to 31 c.c. representing 62 per cent. of the possible catch. Thus, on the tenth day of 20 trials the average efficiency has doubled over what it was at the start. After 25 days more of such practice the average increase above this level is only 7 c.c., bringing the figure to 38 c.c., which is about 75 per cent. of the possible catch. The practice curve is very regular in form and shows no definite indication of orthodox plateaux, and it is evident that the chief part of the rise due to practice can be quickly worked off by 200 or 300 catches, if it is desirable to bring the individual up toward the stage of a practice level. The curve for the coefficient of variability is practically an exact counterpart in form to that for the average catch. At the beginning the variation between catches equals about 34 per cent. and at the tenth day, when the average catch has doubled, the variability has decreased to 19 per cent. or not far from one half, and by the end of the series has decreased to about 14 per cent.¹

It is recognized that the group of subjects employed in this experiment was relatively small and it is hardly justifiable to draw conclusions regarding such matters as the difference between men and women in their efficiency in executing such a pursuit movement. If the individuals are ranked on the basis of their total average catch per day, it is found that of the better nine there were six men and three women, while in the poorer half of the group there were two men and seven women. There were three women poorer than the poorest man, but only one man did better than the most efficient woman. The average difference between the groups of eight men and ten women is shown in Fig. 4 in the light line curves, which are above and below the curve for the general average

¹ The coefficient of variability for other neuro-muscular tests may be found by referring to Benedict, Miles, Roth, and Smith, Carnegie Inst. Wash. Pub. No. 280, 1919, pp. 551 et seq. Examples which may be mentioned are: eye-movement speed, 9 per cent.; eye reactions, 19 per cent.; word reactions, 9 per cent.; and electrical threshold about 6 per cent.

catch (heavy solid line). The curves for the men and for the women are fairly smooth, and maintain about a uniform distance apart, the men on the average catching 4 cc. more than the women.¹

Individual practice curves, such as illustrated in Fig. 5, are naturally less smooth than the average for the whole group. In Fig. 5 results for one of the most efficient and also for one of the least capable subjects have been combined. Subject *C* made very rapid progress, starting with 21 c.c. and rising to 28, 30, 32.4, 35.8, and 36.7 c.c. on the next six successive days. (See Curve 1.) There is a slight decline on the seventh and eighth days and quite a definite decrease on the ninth day. The fluctuations usually range from 1 to 3 c.c. Undoubtedly these variations in the average would have been smaller had the number of trials on each day been larger. For a fairly long period, that is, from the tenth to the twenty-ninth day, the average for Subject *C* is very close to 37 c.c., which is 74 per cent. of the possible catch. The performance during this period may conceivably be classed as a plateau, for there is undoubtedly an indication of a definite stage of improvement following it, during the last six days. The coefficient of variability for Subject *C* (Curve 2) shows rapid improvement at first, corresponding to his improvement in the amount of the catch up to the seventh day. Beyond this time there are fluctuations, some of them quite large. From the seventh to the twentieth day, inclusive, the average variability is about 14 per cent., while from the twenty-first to the thirty-sixth day, although there are several instances as low as 8 or 10 per cent., the average is 12.5 per cent.

Subject *R* did poorly at the start, with an average catch of 8.5 c.c. (see Curve 3) and a variability of 54 per cent. (see Curve 4). Furthermore, poor learning ability is demonstrated by the results for the third and fifth days, when the

¹ Nothing extensive has been done with children. Probably in working with them the excursion of the pendulum should be reduced somewhat from the 70-centimeter swing employed with adults. However, preliminary trials with the apparatus as arranged for adults indicate that a nine-year-old child can catch at the beginning from 10 to 12 c.c. and a six-year-old child from 5 to 6 c.c.

average was in each case slightly lower than on the preceding days. The results show considerable progress between the fifth and the twentieth days, a change from 15.5 to 29 c.c. with some decrease in the variability, although the fluctuations here are quite large. The average for the last five days

C.C. INDIVIDUAL PRACTICE ON PURSUIT PENDULUM.

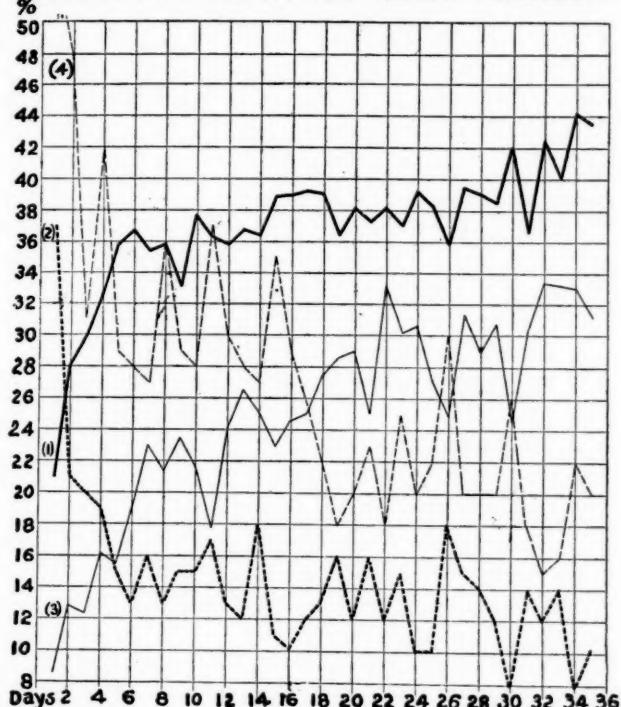


FIG. 5. Individual practice curves showing comparison between two subjects. Curve 1 shows the average catch per day and Curve 2 the average variability per day for one of the most skilful subjects. Curves 3 and 4 show the average catch and variability per day, respectively, for one of the least capable subjects.

is 32.3 c.c., or approximately 65 per cent. of the possible catch, with an average coefficient of variability for these same days of about 18 per cent., in contrast to the 75 per cent. catch and 14 per cent. variability for the total group of adults.

To illustrate a series of measurements made on an individual for the purpose of investigating the effect of some introduced factor on neuro-muscular efficiency the data in Table I are given. The pursuit-pendulum test was one of a number of measurements used in a recent alcohol experiment. This fragment of data is introduced for the sole purpose of illustrating the pursuit pendulum results and in no sense as a contribution to alcohol literature. The complete data are being elaborated for later publication as an alcohol research. The series of eight tests required 30 minutes. Following a light lunch, the subject carried through this series two times in succession. At the end of the second period he drank 1

TABLE I
THE PURSUIT PENDULUM AS A TEST OF NEURO-MUSCULAR EFFICIENCY.
RESULTS SHOWING THE EFFECT OF ALCOHOL

Date	Successive Half-hour Periods					
	1	2	Drink	3	4	5
1919						
Nov. 5.....	c.c.	c.c.				
	1,142	1,120	1 liter water	1,115	1,145	c.c.
Nov. 8.....	1,170	1,152	" " "	1,176	1,191	1,120
						1,185
Nov. 19.....	1,190	1,184	" " "	1,192	1,200	1,190
Nov. 21.....	1,190	1,178	" " "	1,178	1,140	1,148
Nov. 22.....	1,200	1,180	" " "	1,200	1,193	1,192
Av.	1,178	1,163		1,172	1,174	1,167
		1,170		+2	+4	-3
Nov. 6.....	1,178	1,150	1 liter	1,092	1,108	1,096
Nov. 7.....	1,156	1,166	2.75 alc.	1,137	1,122	1,066
Nov. 10.....	1,172	1,185	27.5 grams	1,146	1,130	1,096
Nov. 17.....	1,173	1,173	" "	1,130	1,043	1,065
Nov. 18.....	1,172	1,208	" "	1,107	1,102	1,135
Av.	1,170	1,176		1,122	1,101	1,092
		1,173		-51	-72	-81
				53	76	78
				1,172	1,172	1,172
				4.5	6.5	6.7
Av. loss, 5.9 per cent.						

liter of water, or 1 liter of water in which 27.5 grams of ethyl alcohol had been diluted. The quantity and temperature of the liquid were not varied. Fifteen minutes were quite sufficient in which to drink the liquid. After the liquid was taken,

the series of measurements was repeated three times, that is, periods 3, 4, and 5 of the day. Table I shows data for five normal days, on which only water was taken, and for five other days on each of which 1 liter of a 2.75 per cent. alcohol mixture was consumed. No effort was made to disguise the taste of the alcohol. The subject, an abstainer by habit, was in the best of physical condition. The values in Table I give the total catch in cubic centimeters for 25 cups, as measured by the method of emptying the whole bank of cups at once. (See Fig. 3.) The two preliminary periods for the five days on which water only was taken show total averages of 1,178 c.c. and 1,163 c.c., or a combined preliminary average of 1,170 c.c. (46.8 c.c. per catch), which compare favorably with the two preliminary values, *i.e.*, before alcohol was taken, on the alcohol days, namely, 1,170 c.c. and 1,176 c.c., or a combined average of 1,173 c.c. (46.9 c.c. per catch). Periods 3, 4, and 5 show only minor differences (+ 2 c.c., + 4 c.c., and - 3 c.c.) from the combined preliminary average in the case of normal days. On the alcohol days the differences are all minus, that is, less water was caught after the alcohol was taken by - 51 c.c., - 72 c.c., and - 81 c.c. for the total averages. Subtracting the alcohol differences from those for normal days, it is found that 53 c.c., 76 c.c., and 78 c.c. represent the alcohol effect for periods 3, 4, and 5, respectively. These decrements between normal and alcohol performance, on the basis of 1172 (the grand average for all preliminary trials on both groups of days), equal 4.5, 6.5, and 6.7 per cent., or an average loss of 5.9 per cent., which represents the alcohol effect on this test of coördination. The subject improved somewhat between November 5 and 22, but since there is only slight improvement within the day and the water and alcohol experiments alternate with each other, this practice change is not troublesome. Indeed, the data are very consistent, *e.g.*, at no time following ingestion of alcohol was the subject able to catch as much as he had in the poorer preliminary period for the same day.

A pursuit coördination test, such as has been here described, not only possesses the advantages of requiring very

simple apparatus and of securing quantitative results which are immediately available without the painstaking reading of records, but it appears to have elements comparable to many industrial operations where the task not only requires quick reaction but also that a movement or movements be executed according to a fairly definite pattern. A reaction is usually only the beginning of coördinated movement towards some end or of a series of such coöordinations, and probably in most instances in practical life the adequacy with which the series of coöordinations is carried through is fully as important, if not more so, than the mere matter of speed in initiating them. Especially would this appear to be the case in movements for compensating, directing, aiming, or otherwise tending any moving object, where the pace and pattern are not set entirely by the subject himself. Quickness, precision, and steadiness of movement have long been tested in reference to stationary objects. The pursuit pendulum provides a simple means of measuring these factors in reference to a moving object and thus supplements the general psychological measurement of motor control and capacity. The pursuit test invariably challenges a subject's interest, but practically every one finds it more difficult than he at first expects.

THE LIMITS OF COLOR SENSITIVITY: EFFECT OF BRIGHTNESS OF PREEXPOSURE AND SURROUNDING FIELD

BY C. E. FERREE AND GERTRUDE RAND

Bryn Mawr College

INTRODUCTION

The difficulty of getting reproducible results in determinations of the color sensitivity of the peripheral retina is a common complaint among clinic workers. This difficulty is so great as to lead many seriously to question the value of such determinations in the work of diagnosis. Their value in diagnosing and in checking up the course of some of the most serious affections of the eye is readily conceded, however, provided the needed precision can be attained. The need of greater precision of working in the laboratory, while less important to human welfare, is no less insistent. These combined needs led us several years ago to make a study of the variable factors which influence the chromatic response, the details of which are still in progress. Some of these factors pertain to the control of the stimulus, some are peculiar to the response of the eye itself. All may be standardized and controlled. The normal eye is highly sensitive and complex in its responses but not inherently erratic. While the abnormal eye may be more erratic, one of the symptoms it may be of its abnormality, there should be so far as we can see no essential difference in the technique of the study and of the testing of its functioning. In fact a characteristic difference in this regard, which can be determined with certainty only when other variable factors are controlled, may well be found to serve as a clue to an early diagnosis of its abnormality.

The variable factors which influence the chromatic response of the retina are, so far as we have discovered, the wave-length and the purity of the stimulus, the intensity of

the stimulus and the visual angle, length of exposure of the eye, accuracy and steadiness of fixation, general illumination and state of adaptation of the retina, breadth of pupil, and the brightness of the preëxposure and of the field surrounding the stimulus. We have already published considerable data on the effect of these factors in earlier papers (1). It will be the special purpose of the present paper to deal with the last two, the brightness of the preëxposure and of the surrounding field. A detailed explanation of the effect of these two factors on the amount of the chromatic response has been given in the second of the papers referred to above (1). A brief explanation and statement of principles will suffice here.

I. When a small colored stimulus, surrounded by a field, for example, of white or black is viewed, a sensation is given which consists of the color mixed with black or white, due to a contrast sensation induced from the surrounding field. The effect of fusing a color with white or black is twofold. (a) There is a quantitative effect due to the inhibition of the chromatic excitation by the achromatic. In general, in the central retina at medium and high illuminations, white inhibits color the most, the grays in order from light to dark next, and black the least. Also the amount of the inhibitive action varies with the different colors, with the part of the retina at which the stimulation takes place, and the state of brightness adaptation of the retina. The amount of induction depends upon the difference in brightness between the stimulus and the surrounding field; it increases with the distance from the fovea and with decrease in the general illumination; and, with a given difference in brightness between the stimulus and the surrounding field, it is greater with a white than with a black field—also the amount of increase of induction with decrease of illumination and with increase of distance from the fovea is greater with a white than with a black field. And (b) there is also a qualitative effect. The hue of certain colors is changed by the action of the achromatic excitation. The change is greatest when the stimuli are blue and yellow. For example, yellow when

mixed with black gives a greenish yellow which with the right proportion of components may become an olive green; and blue when mixed with white or light gray gives a sensation of reddish blue.

2. When making the color observation in the peripheral retina, the observer is given a short period of preparation before the stimulus is exposed, in which to obtain and hold a steady and accurate fixation. This introduces the factor of preëxposure for, during this period of preparation, the area which is to be stimulated by color receives a previous stimulation. This previous stimulation, when it differs in brightness from the color, gives a brightness after-image which mixes with the color sensation and both reduces its saturation and modifies its color tone. If the preëxposure is lighter than the stimulus color, it adds by after-image a certain amount of black to the succeeding color impression; if darker, it adds a certain amount of white. Since both white and black as after effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, that is when the preëxposure is of the same brightness as the color. The preëxposure should, therefore, be a gray of the brightness of the color. No brightness after-image will then be added to the succeeding color impression to modify either its saturation or color tone. The only brightness change acting upon it will be due to the slight adaptation to this gray during the short time of preëxposure. Even closing the eye, as is frequently done before stimulating, is equivalent to giving a black preëxposure.

The general principle then is clear. There remains only to explain why in the peripheral retina the short preëxposure which takes place while the eye is obtaining a steady fixation has so much effect on the color stimulation immediately following. Two reasons are found for this. (a) The after-image reaction of the peripheral retina is extremely quick. While some slight variation is found at different angles of excentricity, in general the peripheral after-image seems to reach its maximal intensity with a few seconds of stimulation. This amount of time is usually consumed in obtaining fixa-

tion and preparing for the stimulation, hence in each observation there is fused with the color sensation about as strong a brightness after-image as can be aroused. For this reason alone it is readily seen why the brightness of the preëxposure is of so much greater consequence in the peripheral than in the central retina, where the maximal intensity of after-image is, roughly speaking, obtained from a stimulation of 40-60 seconds or longer. (b) There is apparently no latent period in case of the peripheral after-image. It flashes out at full intensity immediately upon the cessation of the stimulation. Thus there is no possibility of escaping the full effect of the brightness after-image on the stimulus color as might happen in the central retina where the latent period obtains, if there were a very short exposure to stimulus color.

CONDITIONS UNDER WHICH THE WORK WAS DONE

The determinations were made in an optics room of the type described in previous articles (2). The illumination was kept constant at a value at the point of work of 42 foot-candles, vertical component; 31.2 foot-candles, 45 degree component; and 12.5 foot-candles, horizontal component. Three investigations were conducted.

1. A determination was made of the effect on the apparent limits of color sensitivity of variations in the brightness of the field surrounding the stimulus. Three fields were used: the standard white of the Hering series, giving a surface brightness at the intensity of illumination used of 0.0209 candle-power per sq. in.; the standard black of the series, giving a surface brightness of 0.00094 candle-power per sq. in. and grays of the brightness of the color at the limits of sensitivity in each of the meridians investigated. These grays ranged in brightness in the different meridians from 0.00350 to 0.00395 cp. per sq. in. for red; 0.01445 to 0.0189 for yellow; 0.01058 to 0.01185 for green; and 0.00289 to 0.00366 for blue. In order to study the effect of brightness of surrounding field in separation, the preëxposure was in each case made of the brightness of the color at the point of investigation.

2. A determination was made of the effect on the apparent limits of sensitivity of varying the brightness of the preëxposure. Again three brightnesses were used: the standard Hering white; the standard Hering black; and grays of the brightness of the color at the limits of sensitivity in each of the meridians investigated. The photometric value of the white, black and the range of grays for each of the colors are given in 1 above. In this series of experiments the surrounding field was made in each case of the same brightness as the color at the point of investigation.

3. A determination was made of the combined effect of preëxposure and surrounding field on the apparent limits of sensitivity. The same three brightnesses were used as in the preceding investigations. In these cases, however, the surrounding field and preëxposure were both made of the same brightness, *i.e.*, both white, black or grays of the brightness of the color at the limits of sensitivity in the meridians investigated.

Since the results obtained were meant only to be comparative of the effect of varying given factors, it was deemed sufficient to make the determinations with pigment stimuli. So obtained the results are moreover more nearly what may be expected in the work of the clinic. The standard red, yellow, green and blue of the Hering series of papers were used. The work was done with the rotary campimeter described in previous papers (3). With the control of surrounding field afforded by the campimeter, this apparatus combines the rotary features of the perimeter. Without some apparatus combining both of these features we have not found it possible to make a determination of the apparent limits of sensitivity with an adequate control of the brightness of the surrounding field and of the preëxposure. The need of an apparatus in the clinic by means of which this control may be accomplished is obvious. Not only is it impossible to secure an adequate control of these two important factors by means of the standard perimeter, but a very great practical difficulty is encountered in daylight work in getting an equal illumination of the pigment stimulus at

different points in the field of vision and a constant illumination from sitting to sitting. In case of artificial illumination the latter difficulty can perhaps be eliminated with care; but the task of securing an equal effective illumination of the stimulus from point to point in the same meridian and of corresponding points in different meridians is practically impossible in case of any perimeter now in use, because of the unequal shading of the moving stimulus by the observer, the varying inequalities of the incident and reflecting angles, etc. In case of the instrument used by us these difficulties are minimized by using a stationary pigment surface, 20 x 20 cm. placed with special reference to evenness of illumination at some constant distance (in the present work 45 cm.) behind the stimulus opening in the campimeter and by securing the excentric stimulation by shifting the fixation from point to point along an arm specially constructed for the purpose. For other points of criticism of the perimeter as an instrument of precision for either light or dark room work the reader is referred to former papers. The preëxposure was secured by inserting the appropriate pigment surface between the stimulus card and the stimulus opening in the campimeter. The duration of the preëxposure was kept constant at 2 seconds. The stimulus opening in the campimeter was 15 mm. in diameter. At the eye, 25 cm. distant, this subtended a visual angle of $3^{\circ} 26'$.

The more important results given in this paper have been confirmed repeatedly both in the graduate and undergraduate work in our laboratory. The determination of the effect of the brightness of preëxposure and surrounding field on the apparent limits of color sensitivity has in fact formed a part of the drill work in the undergraduate laboratory for several years. Space will be taken here for the results of only one observer—the observer whose results have been given in the preceding studies on the color sensitivity of the peripheral retina.

As has already been indicated, the effect of brightness of the preëxposure and of the surrounding field falls under the general heading of the inhibitive action of the achromatic

excitation on the chromatic. This action takes place however the achromatic excitation is aroused—by the admixture of white light, by after-image, by contrast, etc. It may be strikingly and conveniently demonstrated to large numbers at once in the following lecture room experiments. (a) Set up side by side on three color mixers discs made up of 180 degrees of color, *e.g.* blue, and 180 degrees of white, 180 degrees of blue and 180 degrees of gray of the brightness of the blue, and 180 degrees of blue and 180 degrees of black. When mixed, although the eye receives the same amount of colored light from each set of discs, the mixture with black seems to have lost but very little, if any, color; the mixture with white is a lavender with but little color; and the mixture with gray of the brightness of the color, in this case a very dark gray, is less saturated than the mixture with black. When different grays are used the saturation decreases apparently in graded steps as white is approached. The demonstration can be made on a single color mixer by compounding the color disc with white, black and gray discs of different breadths or radii. When rotated this gives the effect of a surface made up of three concentric zones or rings, one in which the color is mixed with white, one with gray and the other with black. The demonstration may be made roughly quantitative by determining the proportions of color required to give the chromatic threshold in black, white and the grays; also by determining the proportions of color and the achromatic series to give equal saturations.

(b) Prepare a preëxposure surface, half white and half black, 50 x 60 cm. Expose the eye 15–20 seconds and project the after-image on a colored surface, *e.g.*, blue, of the same dimensions. The half of the field preëxposed to black will appear a very pale unsaturated lavender, while the half preëxposed to white will be a dark strongly saturated blue, although the eye receives the same amount of light from both halves of the field. As the after-image dies away the two halves of the field become more and more nearly alike in saturation and color tone. If desired, the preëxposure surface may be made of white, black and a series of graded

grays, appropriately arranged. When this is done the graded loss in saturation due to the different brightnesses of the after-image may be observed. This demonstration also may be made quantitative by finding the threshold of color after the eye has been preëxposed for 15-20 seconds to white, black and the grays.

(c) Prepare contrast discs with narrow rings of color and inside and outside surfaces of black, white and a gray of the brightness of the color, respectively. Set up on color mixers side by side and rotate to smooth out all margins. The colors are lightened and darkened respectively by contrast induced by the black and white fields. The effect of these achromatic excitations on the hue and saturations of the colors is similar to that obtained in the former experiments. A more striking effect is produced if a mixed color, *e.g.*, orange, is used. The quantitative features noted above can also be utilized in this demonstration by employing for the contrast ring in each case a gray of the brightness of the color and enough of the color to give the threshold of color sensation when acted upon by the white and black inductions. The effect of induction and after-image, it will be remembered, are not nearly so striking in the central as in the peripheral retina. Much more induction with a given brightness difference between the inducing and the contrast field, for example, is produced in the peripheral retina, and only a short period of preëxposure (2-3 seconds) is required to give a strong after-image with no latent period.

RESULTS

The following results were obtained: (1) The widest angular limits of the color zones were obtained when the preëxposure and surrounding field were of the same brightness as the color. (2) When the brightness of preëxposure and surrounding field were different from that of the color, the effect of surrounding field was less than that of preëxposure; and the effect of either is always less than the combined effect of both. (3) In some meridians the effect of surrounding field alone narrowed the limits as much as

11 degrees; the effect of preëxposure alone, as much as 17 degrees; and the combined effect of preëxposure and surrounding field, as much as 20 degrees.

(4) The amounts the limits were narrowed for red, yellow, green and blue, respectively, by a white preëxposure alone ranged in the different meridians¹ from 4-15 degrees, 2-17 degrees, 3-15 degrees, and 4-12 degrees; by a black preëxposure from 3-11 degrees, 3-10 degrees, 4-13 degrees, and 2-12 degrees; by a white surrounding field 1.5-10 degrees, 2-9 degrees, 2-11 degrees, and 2-10 degrees; by a black surrounding field 1-8 degrees, 1-8 degrees, 2-10 degrees, and 1.5-9 degrees; by a combined white preëxposure and white surrounding field 5-19 degrees, 2-20 degrees, 4-20 degrees, and 5-17 degrees; by a combined black preëxposure and black surrounding field 4-17 degrees, 5-12 degrees, 7-18 degrees and 5-18 degrees. When the effect of a white or black surrounding field alone was wanted, the preëxposure was made of the same brightness as the color at the point of investigation; similarly when the effect of a white or black preëxposure was wanted, the surrounding field was made of the same brightness as the color at the point of investigation. The value of the limits with a preëxposure and surrounding field of the same brightness as the color served in each case as the standard value in terms of which to estimate the amounts the limits were narrowed by the white and black preëxposures and surrounding fields and their combinations.

These values, it will be remembered were obtained with a very precise control of the illumination of the working surfaces. It is obvious that a much greater variability of result should be expected had there been no better control of the constancy of illumination than is ordinarily exercised in office and clinic work, and too often in laboratory work. The effect on both the limits and hue of the color of such variations in the daylight illumination of the working surfaces as are apt to occur over long periods of time when no especial control is exercised, will be given in a later paper.

¹In the order shown in the tables.

In order to realize how profoundly the powers of chromatic response must have been affected to change the limits of sensitivity by the amounts represented by the above figures one must bear in mind how abruptly sensitivity falls off in the far periphery of the retina. A determination of the thresholds of color in the temporal meridian with preëxposure

TABLE I

LIMITS OF COLOR FIELD FOR RED

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Red

Meridian	Effect of Preëxposure ¹			Effect of Surrounding Field ²			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°.....	58	45	47	58	48	50	58	40	41
Nasal 25°.....	49	43	43	49	46	46	49	41	39
" 45°.....	49	43	41	49	46	44	49	38.5	37.5
" 70°.....	47	43	42.5	47	45.5	44.5	47	41	40
" 90°.....	43	38	37	43	41.5	40	43	38	38
" 110°.....	47	42	42	47	43	43	47	41	42.5
" 135°.....	50	46	45	50	48	47	50	45	44
" 155°.....	51	47	47	51	48.5	48.5	51	46	46
Lower 180°.....	60	53	56	60	55	57	60	52	56
Temporal 25°	73	59	68	73	66	70	73	55	62
" 45°	79	64	74	79	70	76	79	60	72
" 70°	85	75	80	85	80	82	85	69	78
" 90°	89	83	85	89	85	88	89	80	84
" 110°	89	82	85	89	84	86	89	80	83
" 135°	85	78	82	85	81	83	85	77	81
" 155°	75	62	65	75	65	68	75	60	64

and surrounding field of the same brightness as the color for red, yellow, green and blue at 5 degrees, 3 degrees, 2 degrees and 1 degree respectively from the limit shows the following values: for red, 132, 150, 250 and 320 degrees; for yellow, 100, 150, 240 and 330 degrees; for green 130, 145, 260 and 345 degrees; and for blue 130, 145, 200 and 310 degrees.

¹ In determining the effect of the different brightnesses of preëxposure, the brightness of the surrounding field was made equal to that of the color at the point of investigation.

² In determining the effect of the different brightnesses of surrounding field, the brightness of the preëxposure was made equal to that of the color at the point of investigation.

For red thus there was an increase of 172.7 per cent. in the threshold in passing to the limit from a point 5 degrees from the limit; for yellow an increase of 260 per cent.; for green an increase of 207.7 per cent.; and for blue an increase of 207.7 per cent. For a more detailed experimental analysis of the effect of preëxposure, surrounding field, intensity of

TABLE II

LIMITS OF COLOR FIELD FOR YELLOW

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Yellow.

Meridian	Effect of Preëxposure ¹			Effect of Surrounding Field ²			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White		Gray of Brightness of Color	White		Gray of Brightness of Color	White	
		Black	Black		Black	Black		Black	Black
Upper 0°.....	47	41	37.5	47	41	39	47	38	36
Nasal 25°.....	42	39	38	42	40	39	42	38.5	37
" 45°.....	42	37	36	42	40	38	42	37	35.5
" 70°.....	46	42	40	46	44	42	46	42	39
" 90°.....	44	42	40	44	42	41	44	42	38.5
" 110°.....	46	42	38	46	43	41	46	41	37
" 135°.....	50	46	45	50	48	47.5	50	46	45
" 155°.....	48	44	44	48	46	46	48	43	43
Lower 180°.....	59	51	54	59	53	56	59	47	52
Temporal 25°.....	65	48	55	65	58	61	65	45	53
" 45°.....	73	63	70	73	68	72	73	62	67
" 70°.....	87	70	84	87	79	86	87	69	80
" 90°.....	89	75	85	89	80	87	89	72	84
" 110°.....	89	81	86	89	83	87	89	80	85
" 135°.....	87	80	84	87	82	85.5	87	78	84
" 155°.....	72	60	65	72	63	67	72	59	63

the illumination of the visual field, amounts of induction with different brightness relations of surrounding field to stimulus at different intensities of illumination, etc., and the effect of all of these on the thresholds of color and the limits of sensitivity the reader is referred to the first two papers cited in the appended bibliography (1).

5. In those meridians in which the limits are wide there is a general tendency for the white preëxposure and surrounding field to narrow the limits more than a black preëxposure

¹ Brightness of Surrounding Field: gray of the brightness of yellow.

² Brightness of Preëxposure: gray of the brightness of yellow.

and a black surrounding field. We have stated in our introduction that the amount of inhibition of the chromatic by the achromatic excitation varies with the color, the part of the retina stimulated and the state of adaptation of the retina. This statement applies also to the relative effects of white and black. In the central retina at medium and high illuminations white inhibits color much more than black.

TABLE III

LIMITS OF COLOR FIELD FOR GREEN

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Green

Meridian	Effect of Preëxposure ¹			Effect of Surrounding Field ²			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°.....	36	26	29	36	28	31	36	27	22
Nasal 25°.....	35	30	27	35	31	29	35	26	21
" 45°.....	38	30	28	38	32	30	38	29	24
" 70°.....	39	34	31	39	36	31	39	32	27
" 90°.....	39	35	33	39	37	35	39	33	28
" 110°.....	37	31	31	37	33	33	37	31	30
" 135°.....	37	32	29	37	34	31	37	31	25
" 155°.....	33	30	29	33	31	30	33	29	26
Lower 180°.....	37	32	31	37	34	33	37	28	26
Temporal: 25° ..	37	30	30	37	34	35	37	28	26
" 45° ..	42	34	36	42	39	40	42	30	33
" 70° ..	61	51	53	61	56	57	61	47	50
" 90° ..	69	56	60	69	60	62	69	50	53
" 110° ..	65	53	56	65	58	61	65	46	50
" 135° ..	57	42	44	57	46	47	57	37	39
" 155° ..	44	39	37	44	41	39	44	35	34

At these illuminations therefore a black preëxposure and surrounding field are much more unfavorable than white. At lower illuminations this difference in effect becomes less pronounced. In the far periphery of the retina the following are some of the conditions which contribute to make black as preëxposure and surrounding field give wider limits of sensitivity. (a) A condition of low illumination and a state of low illumination adaptation. (b) A darkening of all of the

¹ Brightness of Surrounding Field: gray of the brightness of green.

² Brightness of Preëxposure: gray of the brightness of green.

colors, particularly red and yellow (the Purkinje shift of the peripheral retina). This brings the brightness of the color nearer to black than to white and the stronger relative darkening of red and yellow than of their neutral or colorless preexposures and surrounding fields, increases the contrast

TABLE IV

LIMITS OF COLOR FIELD FOR BLUE

Showing the Effect of Brightness of Preexposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preexposure and Surrounding Field on the Apparent Limits for Blue

Meridian	Effect of Preexposure ¹			Effect of Surrounding Field ²			Combined Effect of Preexposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°.....	52	40	46	52	42	48	52	35	34
Nasal 25°.....	45	39	39	45	41	42	45	38	36.5
" 45°.....	48	44	46	48	45	46	48	40	40
" 70°.....	46	41	41	46	44	44	46	41	41
" 90°.....	52	42	42	52	48	47	52	42	40
" 110°.....	50	46	45	50	47.5	47	50	44	43
" 135°.....	52	47.5	47.5	52	50	49	52	46	46
" 155°.....	58	48	46	58	51	49	58	43	42
Lower 180°.....	70	63.5	62	70	66	64.5	70	61	59
Temporal: 25° ..	70	62	65	70	65	68.5	70	56	59
" 45° ..	79	71	73	79	73	75	79	65	69
" 70° ..	86	78	82	86	80	84	86	77	80
" 90° ..	91	86	85	91	89	89	91	84	84
" 110° ..	91	85	85	91	88	88	91	83	83
" 135° ..	89	84	83	89	86	85	89	83	83
" 155° ..	80	75	75	80	77	77	80	75	74

and after-image effect for white and decreases it for black. The darkening of red and yellow in passing to the far periphery of the retina is very great. In the nasal half of the retina with its wide limits, the effect of this darkening on the results of our determinations was, of course, the most pronounced. As colors darken, there is, when a certain point in the process is reached, varying with the color, a tendency for them to lose their saturation very rapidly. (c) Achromatic induction increases very strongly with decrease of illumination and therefore increases in passing from the center to the periphery

¹ Brightness of Surrounding Field: gray of the brightness of blue.

² Brightness of Preexposure: gray of the brightness of blue.

of the retina. It increases much faster for white than for black.

In the meridians in which the limits are narrower the situation is more nearly as it is in the central retina. Here the tendency is for the limits to be narrowed more by a black

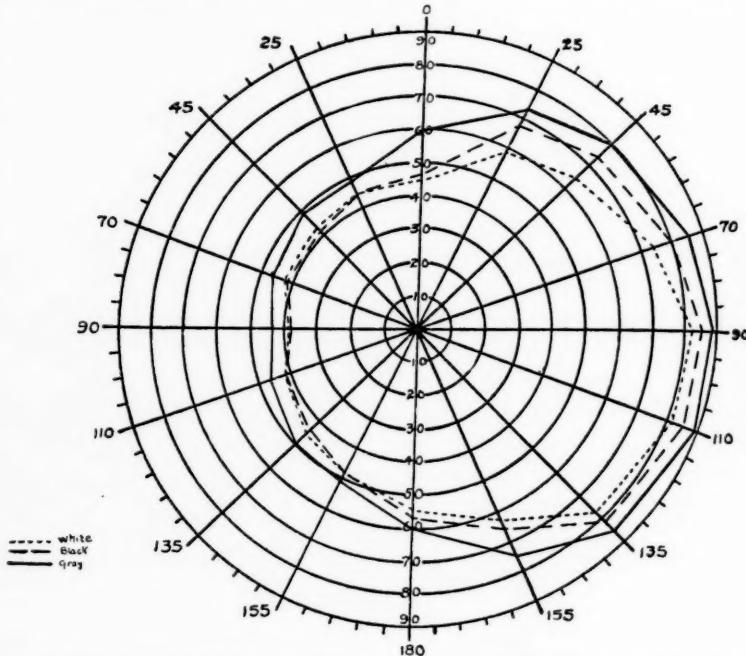


FIG. 1. Effect of brightness of preexposure on the limits of the color field. In this chart are shown the apparent limits for red with preexposures respectively of white, black, and gray of the brightness of the color at the point of investigation, surrounding field in each case gray of the brightness of the color at the point of investigation.

than by a white preexposure and surrounding field. In some meridians the amount of narrowing is approximately equal for both. Another factor which tends to make the effect more nearly the same in these meridians for all backgrounds and preexposures is the more abrupt falling off in sensitivity. That is, more effect on sensitivity is required here to change the limits by a detectable amount than is

required in those portions of the retina where the sensitivity grades off more slowly.

A detailed representation of the results is given in Tables I-IV. and a graphic representation of a part of the results in Figures 1-6. In the tables results are given separately

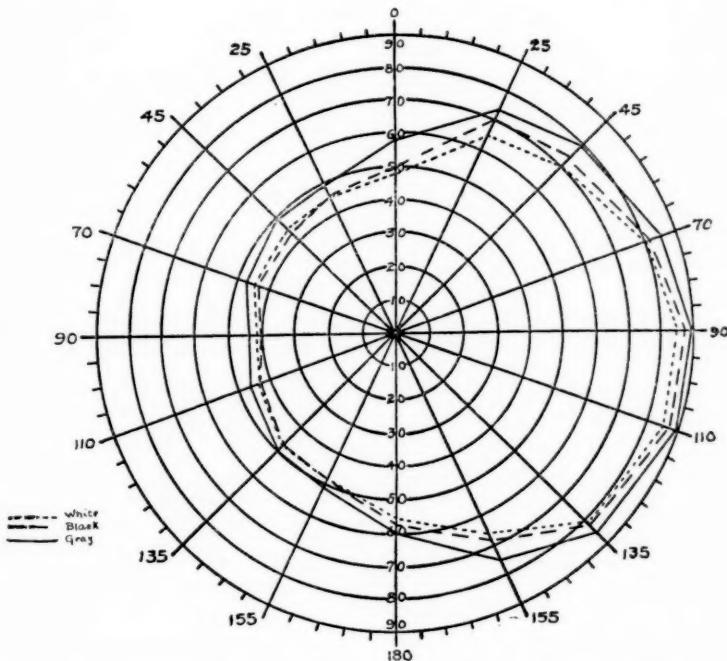


FIG. 2. Effect of brightness of surrounding field on the limits of the color field. In this chart are shown the apparent limits for red with a surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation, pre-exposure in each case gray of the brightness of the color at the point of investigation.

for the effect of preexposure, surrounding field and combined effect of preexposure and surrounding field for each of the four colors: red, yellow, green and blue. In case of the figures, however, space has been taken to represent separately the effect of preexposure and surrounding field for only one of the colors, red—Figs. 1-3. Figs. 3-6 show

the combined effect of preëxposure and surrounding field on each of the four colors. In our previous papers the representation of results has been in terms of position on the retina. In this paper the representation has been made in terms of field of vision.

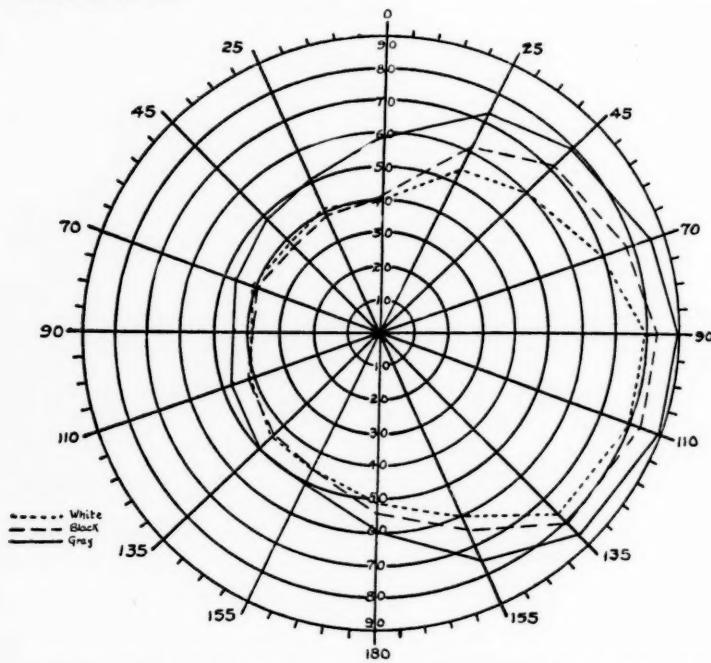


FIG. 3. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for red with both preëxposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

CONCLUSION

It is quite obvious from the preceding data that reproducible results can not be hoped for in perimetric or campimetric determinations of the sensitivity of the peripheral retina unless the variable effects of preëxposure and surrounding field be eliminated from the conditions of work. This can be done completely only by making the brightness of

the preëxposure and surrounding field in each case the same as that of the color employed and working under constant intensity of illumination. Among the effects of a variable intensity of illumination on the results of a perimetric or campimetric determination the following two may be men-

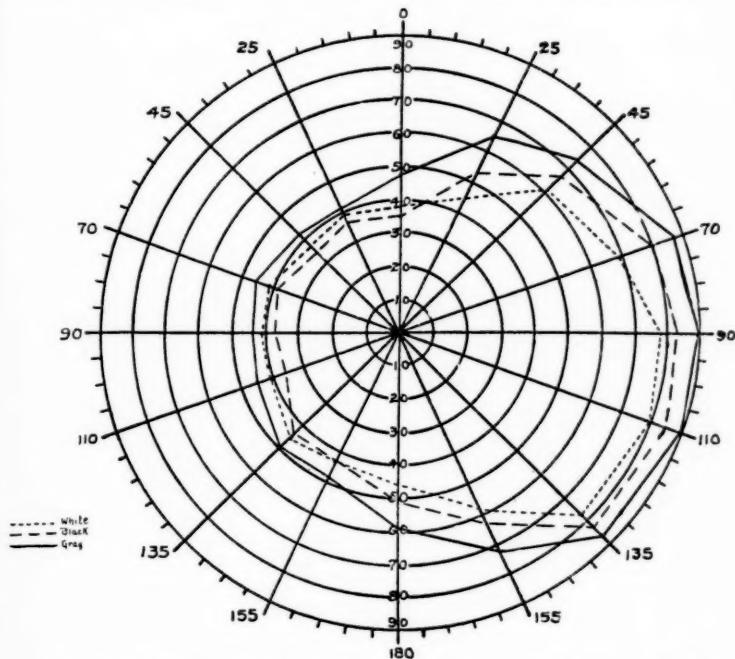


FIG. 4. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for yellow with both preëxposure and surrounding field respectively of white, black, and the gray of the brightness of the color at the point of investigation.

tioned. (a) When the color stimulation is given by light reflected from pigment stimuli of a given coefficient of reflection the amount of colored light obtained depends upon the intensity of light incident on the reflecting surface. And (b) a brightness match of preëxposure and surrounding field with the stimulus surface will not hold at different illuminations (the Purkinje phenomenon).

We have worked out in previous papers the conditions under which the desired standardization of intensity and color value of illumination and control of brightness of pre-exposure and surrounding field may be obtained in labor-

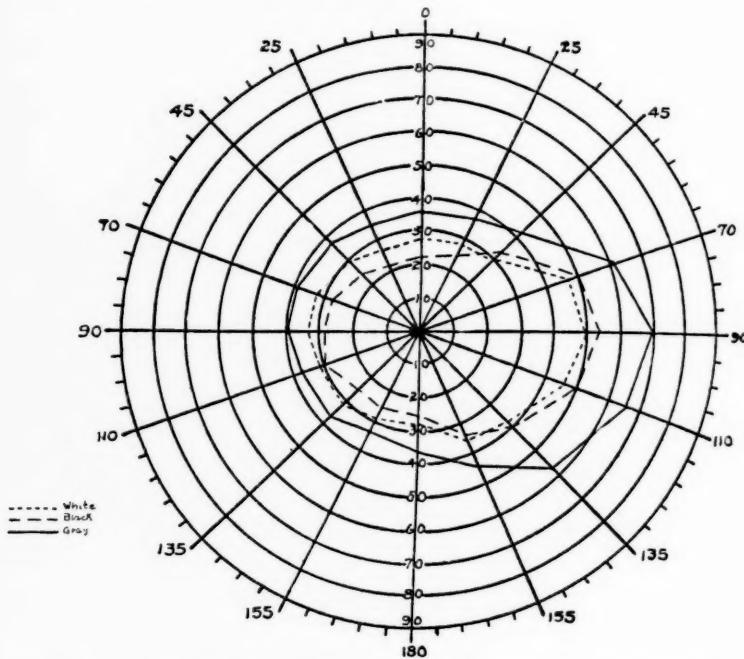


FIG. 5. The combined effect of brightness of pre-exposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for green with both pre-exposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

atory campimetry (4). These conditions however are scarcely feasible for the work of the office or clinic. We have therefore more recently devised and constructed a perimeter by means of which equal illumination of the stimulus is received at every point on the perimeter arm in all meridians and the effect of brightness of pre-exposure and surrounding field can be eliminated with an ease and speed of manipulation which

should be feasible for office and clinic work and with a completeness of result that should be adequate for this type of work. We have in fact constructed two types of perimeter either one of which provides for the uniform illumination of the arm of the perimeter. The perimeters will be described in a later paper.

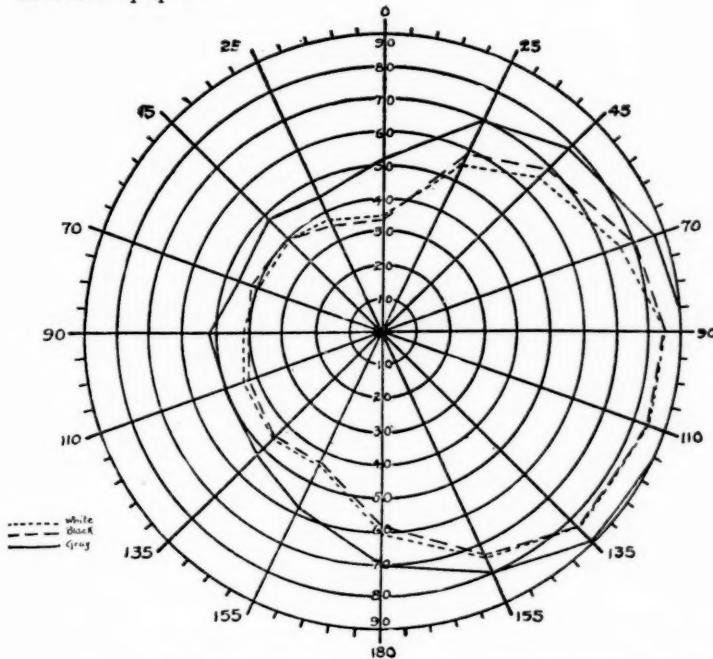


FIG. 6. The combined effect of brightness of pre-exposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for blue with both pre-exposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

COMMENT

A much more detailed study of the quantitative relations of the chromatic and achromatic components of the visual sensation for different intensities of stimulus and for different states of the reacting eye is needed. There are many important practical bearings of the knowledge that would be

gained by such a study. For example, it is often deemed sufficient to give a colorimetric specification of a light at one intensity alone in spite of the fact that the saturation, even the hue of the color, changes with the intensity as well as the composition of the light. We are all familiar in a general way with the fact that even the sensation aroused by a spectrum band of light begins as achromatic or colorless at very low intensities, passes through saturation and hue changes with increase of intensity of light and finally becomes colorless again at high intensities. We have pointed out many times in connection with problems of lighting (5) that while a specification of the composition of light is independent of intensity, a true colorimetric specification may not, depending on the method used, be definite unless it is accompanied also with a specification of intensity. Filters designed to give a certain coloration of light can not be depended upon to give this subjective coloration at all intensities even though the wave-lengths transmitted are in the same proportions. Indeed when used in connection with the same intensity of source the coloration of the illumination of an object as seen by the eye, particularly the saturation, will vary at different distances from the source. The lack of realization of this dependence of the color of light on its intensity as well as its composition has doubtless played no small part in the popular confusion which exists as to the comparative color values of different artificial lights and of the closeness of approximation of certain artificial lights to daylight. The surface of a Welsbach mantle, 0.7 per cent. ceria, viewed directly is, for example, whitish; but the reading page illuminated by it to ordinary working brightness appears distinctly yellowish green. Again the illumination given by the blue bulb lamp may be judged of different color values depending upon the intensity of light falling on the illuminated object. Complementary colors combined to gray at medium or high intensities may not be seen as colorless at low illuminations, e.g., the gray produced by combining the Hering standard blue and yellow under daylight of good intensity becomes dis-

tinctly lavenderish under the same light at low intensities. Daylight itself is popularly said to become bluish at low intensities. Examples may thus be multiplied indefinitely of the apparently peculiar complexity of the selectiveness of the eye's chromatic response to intensity.

In addition to the practical bearings of the shifting of the quantitative relations of the achromatic and chromatic components in the visual sensation, with no change in the composition of light, there is the interesting problem of explanation. Many factors, it may be, are operative in the production of this phenomenon: a selectiveness of response to intensity, perhaps even a change in the range of the eye's chromatic response to wave-length with change of intensity, in case of spectrum lights; this and slight variations for change of intensity, in the cancelling proportions of the complementary colors and in the mutually inhibitive actions of the non-complementary colors, in case of mixed lights; a direct action of the achromatic excitation on the chromatic, for both simple and mixed lights; etc. It seems not only reasonable but necessary to infer this latter action because the same type of effect is produced on the color when the achromatic component of the sensation is varied in all of the following ways: by keeping the composition of the light the same and varying its intensity, by adding colorless light, by adding white or black to the sensation as after-image or contrast, and by the achromatic changes in adaptation. No other explanation seems possible when the phenomenon is produced as an effect of preëxposure and surrounding field or as we commonly say by after-image and contrast, as has been the case in the work reported in this paper.

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